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**RENEWABLE ENERGY IN MONTANA:  
RESOURCE POTENTIAL AND COMPLEMENTARITY**

By

Elizabeth Mulligan Hartsoch

B.Sc. Gonzaga University, 1998

presented in partial fulfillment of the requirements

for the degree of

Master of Arts

The University of Montana

August 2004

Approved by:

A handwritten signature in black ink, appearing to read "S. J. Stue", is written over a horizontal line. The signature is stylized and cursive.

Dean, Graduate School

8-31-04

Date



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**Renewable Energy in Montana: Resource Potential and Complementarity**

Director: Jeffrey A. Gritzner **JAG**

The potential of renewable energy resources including wind, watercourse, insolation, geothermal and biomass was estimated for the state of Montana. Seasonal variation in wind, watercourse and insolation resources was represented in monthly resource potential estimates. Existing data was used for all estimates. Monthly wind and watercourse potential were estimated using annual resource potential estimates and annual and monthly point data for actual resource availability.

Resources were aggregated according to their energy quality. Low quality energy resources, which are conducive to heating applications, including insolation, geothermal, and biomass, were aggregated as monthly and annual heating resource potential. All five resources were aggregated as monthly and annual electric resource potential.

Results are presented in maps and discussion.

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## **ABBREVIATIONS**

<b>Btu</b>	<b>British thermal unit</b>
<b>DG</b>	<b>distributed generation</b>
<b>EPA</b>	<b>United States Environmental Protection Agency</b>
<b>INEEL</b>	<b>Idaho National Engineering and Environmental Laboratory</b>
<b>kg</b>	<b>kilogram</b>
<b>kW</b>	<b>kilowatt</b>
<b>LMOP</b>	<b>Landfill Methane Outreach Program</b>
<b>m</b>	<b>meter</b>
<b>MW</b>	<b>megawatt</b>
<b>MWh</b>	<b>megawatt hour</b>
<b>NREL</b>	<b>National Renewable Energy Laboratory</b>
<b>SMUGL</b>	<b>Southern Methodist University Geothermal Laboratory</b>
<b>USGS</b>	<b>United States Geological Survey</b>
<b>W</b>	<b>watt</b>
<b>WIP</b>	<b>waste in place</b>

## CHAPTER ONE

### INTRODUCTION

Montana's economy and populace are currently dependent upon fossil fuels and large-scale hydroelectric dams for energy. After decades of paying low prices for these resources, the negative externalities of pollution and dependency upon foreign sources, complicated by the recent deregulation of energy utilities, have created uncertainty and volatility in the market. The massive transmission and distribution grid that delivers electricity to the majority of users in the United States is nearly impossible to secure, and vulnerable to both malicious and accidental outages. These energy sources increase land degradation, pollution, and global climate change; alter the rivers that sustain our communities and cultures; introduce hazards to those downstream; negatively affect fish populations; and leave us vulnerable to malicious acts. Additionally, the social and environmental costs of oil production frequently outweigh the economic benefit in oil exporting countries.<sup>1</sup> It is imperative that we replace these energy sources, as appropriate, with alternative energy sources. The distributed generation (DG) of appropriate energy forms, fueled by locally available, renewable resources, addresses

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<sup>1</sup> Jeffrey Allman Gritzner, Professor of Geography, The University of Montana, personal communication 2 July 2004.

these problems by localizing control of energy production and significantly reducing associated negative externalities.<sup>2</sup>

Montana is rich in natural resources, including the viable energy sources considered in this paper: wind, watercourse<sup>3</sup>, insolation, geothermal and biomass.<sup>4</sup> A concerted effort to utilize these resources in Montana will require quantification and distribution analysis. Specifically, this study focuses upon resources suitable for non-transportation energy, including electricity, heating, and mechanical work.

Several recent studies have undertaken similar goals at varying scales and levels of analysis, but none have addressed seasonal complementarity<sup>5</sup> of resources or compared the potential of watercourse energy to that of other alternatives. Additionally, DG siting and planning will require appropriate data, as well as analysis of spatial distribution and seasonal resource complementarity. This paper will incorporate the most current data on the spatial and seasonal distribution of the above-mentioned resources in Montana, and consider two questions. First, what is the pattern of spatial distribution by month? Then,

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<sup>2</sup> The Winter 2003 issue of Montana Business Quarterly contained an article titled "Distributive Energy: Montana's New Frontier" which supports the argument that Montana is particularly well suited to benefit from distributed energy due to its resource base and rural nature. The article also details a strategy for transitioning to distributed renewable energy by first utilizing locally available natural gas and other fossil fuels and then switching to renewables. Brian Gurney, Mary McNally, and Monte Smith, "Distributive Energy: Montana's New Frontier," *Montana Business Quarterly* (Winter 2003): *passim*.

<sup>3</sup> See discussion of hydropower facilities in the hydropower section of the Theoretical Background chapter of this paper.

<sup>4</sup> John Nielsen, Susan Innis, Leslie Kaas Pollock, Heather Rhoads-Weaver and Angela Shutak, *Renewable Energy Atlas of the West* (San Francisco: The Energy Foundation, 2002), 43.

<sup>5</sup> Throughout I use the term "complementary" to describe the opposing availability of seasonal resources that can result in higher and more continuous availability of local resources for electric- and heat-energy generation. Insolation, which is seasonally high in the summer and low in the winter, may complement wind, which is seasonally high in the winter and low in the summer. High stream flows in the spring provide a third complement.



how does the seasonal variability of each resource allow them to form complements in energy-generation scenarios?<sup>6</sup>

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<sup>6</sup> Readers should be advised that energy potential calculated in this paper is the maximum available at a given location. The actual amount available for a given task will be dependent upon the task and the technology used. It is assumed that end-uses will be satisfied by either electricity or heat. Additionally, the maximum potential may not be useable given renewability criteria. The quantity of a resource that can be extracted renewably depends upon individual location circumstances.

**PART I**  
**OVERVIEW**

## CHAPTER TWO

### THEORETICAL BACKGROUND

Energy sources that currently meet the electricity demands of Montana residents and businesses are primarily coal, petroleum, and large-scale hydropower. In 2000, 34% of the energy used in Montana was generated from coal, 12% from natural gas, 32% from petroleum, and 19% from large-scale hydro. Less than 4% is derived from wood, waste, geothermal, solar and wind.<sup>7</sup> As mentioned above, coal and petroleum are fossil fuels associated with air and water pollution, as well as greenhouse gas emissions.<sup>8</sup> Traditional, large-scale hydropower dams have been associated with declines in fish populations, general changes in waterway characteristics, inundation of cultural and historical sites, and have introduced hazards to those downstream.<sup>9</sup> Additionally, the electric transmission and distribution system that currently delivers power to homes and businesses – better known as the “grid” – is aging and vulnerable to interruptions, both

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<sup>7</sup> U.S. Department of Energy, Energy Information Administration, “Montana,” in *Individual State Data* [database on-line] (Washington D.C.: 2003, accessed 18 March 2003); available from [http://www.eia.doe.gov/emeu/states/main\\_mt.html](http://www.eia.doe.gov/emeu/states/main_mt.html).

<sup>8</sup> A.P. Mitra, Lidia Morawska, Chhemendra Sharma, and Jim Zhang, “Chapter Two: Methodologies for Characterization of Combustion Sources and for Quantification of the Emissions,” *Chemosphere* 49, no. 9 (2002).

<sup>9</sup> James Maxwell, Jennifer LeeForrest Briscoe, Ann Stewart, and Tatsujiro Suzuki, “Locked on Course: Hydro Quebec’s Commitment to Mega-Projects,” *Environmental Impact Assess Rev* 17 (1997), *passim*; Blaine Harden, *A River Lost* (New York: W. W. Norton and Company, 1996), *passim*.

accidental and malicious.<sup>10</sup> While these sources have many negative qualities, they have persisted as the conventional, mainstream option for several social, political, and economic reasons. Industrialization led to widespread replacement of animal power and biomass fuel with fossil fuels. At the time, fossil fuels and electricity were considered efficient and progressive.<sup>11</sup> When oil prices increased dramatically in the 1970s, fossil fuels and electricity had been inexpensive for long enough that an infrastructure had grown to depend upon their use. At the time, the sharp increase in price, and growing awareness of negative impacts sparked much debate and investigation into other options, led primarily by Amory Lovins. When the crisis ended shortly thereafter, the path of least resistance led back to fossil fuels. Socially, the use of fossil fuels and electricity is, to this day, associated with progress, wealth, and personal gain, while alternative sources of energy are associated with counter-culture views and lifestyles.<sup>12</sup> In this time of increased dependence upon foreign-energy sources, threats of terrorism, and compounding environmental effects, prudence encourages investigation of other options.

Much environmental degradation and vulnerability associated with our current energy is avoidable without diminishing the services provided by energy. The theory that has most influenced policy in the last half-century asserts that the more energy we use,

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<sup>10</sup> Thomas E. Hoff and Matthew Cheney, "The Potential Market for Photovoltaics and Other Distributed Resources in Rural Electric Cooperatives," *Energy Journal* 21, no.3 (2000), 1; Deborah R. Feder, "Beyond Conventional Energy Use: A Regionally Based End-Use Approach for the Twenty-First Century" (Ph.D. diss., The Pennsylvania State University, 2001), 161.

<sup>11</sup> Feder, "Beyond Conventional Energy Use", 150.

<sup>12</sup> Ibid.

the better, with an emphasis upon using high-quality<sup>13</sup> energy sources, such as electricity, to do everything.<sup>14</sup> Choosing an energy source that is inappropriate for a particular end use can lead to major inefficiencies. Of the total energy available in fuel at a centralized electric-generation facility, an average of only one third used to provide end-use services, the rest is lost in inefficiencies of generation, distribution, and end-use appliances.<sup>15</sup>

Electricity itself is not the end, but a means for gaining other amenities and services such as heat, motion, or entertainment.<sup>16</sup> The key to getting more services for lower quality or lesser amounts of energy lies in matching end-uses to appropriate forms of energy.<sup>17</sup> Many electronic devices, like computers, require electricity, but other things, like space heating can be accomplished more efficiently through locally available low-quality energy sources such as solar radiation or biomass.<sup>18</sup> When Amory Lovins (widely considered to be the foremost innovator of alternative-energy theories in the United States) advanced this theory in the 1970s, it altered the energy discourse. Opinions were deeply divided on the topic, but it served to expose the theory in a broad arena.<sup>19</sup>

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<sup>13</sup> High quality energy is concentrated, controllable, and easily converted into other forms. Examples are oil, gas, electricity, and coal; Russell Mills and Arun Toke, *Energy, Economics and the Environment* (Englewood Cliffs, New Jersey: Prentice Hall, 1985), 29.

<sup>14</sup> Amory Lovins, *Soft Energy Paths: Toward a Durable Peace* (Cambridge, MA: Ballinger Publishing Company, 1977), 4.

<sup>15</sup> Thomas E. Hoff, Christy Herig, and Robert W. Shaw Jr., "A MicroGrid with PV, Fuel Cells, and Energy Efficiency" in *Proceedings of the 1998 American Solar Energy Society Annual Conference*, Albuquerque, June 14-17: 226.

<sup>16</sup> Lovins, *Soft Energy Paths*, *passim*.

<sup>17</sup> Feder, "Beyond Conventional Energy Use", 94; Lovins, *Soft Energy Paths*, *passim*.

<sup>18</sup> Feder, "Beyond Conventional Energy Use", 143; Lovins, *Soft Energy Paths*, *passim*.

<sup>19</sup> Feder, "Beyond Conventional Energy Use", 138.

In addition to increasing efficiency and providing a better match of energy quality to end use, the distributed generation of electricity from locally available renewable resources is a viable alternative to maintenance and extension of the existing transmission and distribution grid.<sup>20</sup> The term “distributed generation” specifically refers to the strategic siting of electric or heating generation facilities in close proximity to local renewable resources and a demand center. Power companies can save money and increase the security of electricity supply by taking advantage of the independent and efficient qualities of small, distributed generation facilities.<sup>21</sup> Using locally available renewable-fuel sources provides opportunity for a value-added product and local management.

Criteria for qualifying resources as renewable are often debated. This study will consider five resources that can be managed to meet the following criteria: (i) Energy potential can be maintained indefinitely, (ii) Minimize and internalize waste and other environmental impacts, and (iii) Reasonable proximity to end-use to minimize losses associated with transportation.

The five resources considered can be compared across continua of ease of storage and energy matching properties. Wind, insolation, and geothermal energy must be converted to another form to be stored, and therefore are most efficiently utilized immediately, as electricity, heat, or mechanical work. Watercourse energy can be stored

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<sup>20</sup> Thomas E. Hoff, Howard J. Wenger and Brian K. Farmer. "Distributed Generation: An Alternative to Electric Utility Investments in System Capacity," *Energy Policy* 24, no. 2 (1996): 133.

<sup>21</sup> Hoff, "The Potential Market", *passim*; Amanda J. Davis, "Distributed Generation Using Small-Scale Hybrid Wind/Photovoltaic" (D.Eng. diss., University of Massachusetts, 2000), *passim*.

behind a dam, but this requires a dam, and interrupts the waterway. Biomass is most easily stored for later use either in its original form or when converted to methane or ethanol. It is most critical then, to evaluate the seasonal complementarity of the other four resources. Three of these four, excluding geothermal, are highly seasonal. Geothermal potential is not influenced by seasons, though it may fluctuate for other reasons.<sup>22</sup> In terms of energy matching, wind is a form of kinetic energy, and is most efficiently used for mechanical work or when converted to electricity – as in most large-scale applications. Depending upon the location and application, insolation can be captured as heat or as electricity. Geothermal energy is in the form of heat, and is most efficiently used for heating purposes, though some sites with very high temperatures, high potential, and minimal local heating demand are suitable for electricity production. Watercourse energy is kinetic and, like wind energy, most efficiently used for mechanical work or when converted to electricity. Biomass is chemical energy that is most often released through burning, or digesting to methane or ethanol and then burning, making it most suitable for heating applications, and possibly co-firing in fossil fuel electricity plants. Wind is available day and night, and nearly continuously over the landscape, but is seasonally and unpredictably unavailable (owing to weather). Watercourse energy is available day and night, but is highly concentrated on the landscape in usable form, and is seasonally unavailable. Solar resource is only available during the day, is seasonally variable, and locally variable based upon weather.

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<sup>22</sup> Maria Richards, Southern Methodist University Geothermal Laboratory, personal communication, November 2003.

Additionally, four of the five resources considered here are based upon the flow of something from one location to another; air from areas of higher to lower pressure, water to lower elevation, solar radiation from the sun to the earth, or superheated water from internal heating of the earth to the surface. The potential of these resources in a given location, therefore, could be related to use of the resource elsewhere. For example, building a dam upstream of a stream segment with an estimated potential of one kilowatt will likely lower the potential of the downstream segment. Biomass is an arguable exception to this because removing residues or waste in one location does not necessarily reduce the potential of adjacent locations.

Figure 1 depicts watts per square meter of the three seasonally variable resources throughout the year at a site near Helena.

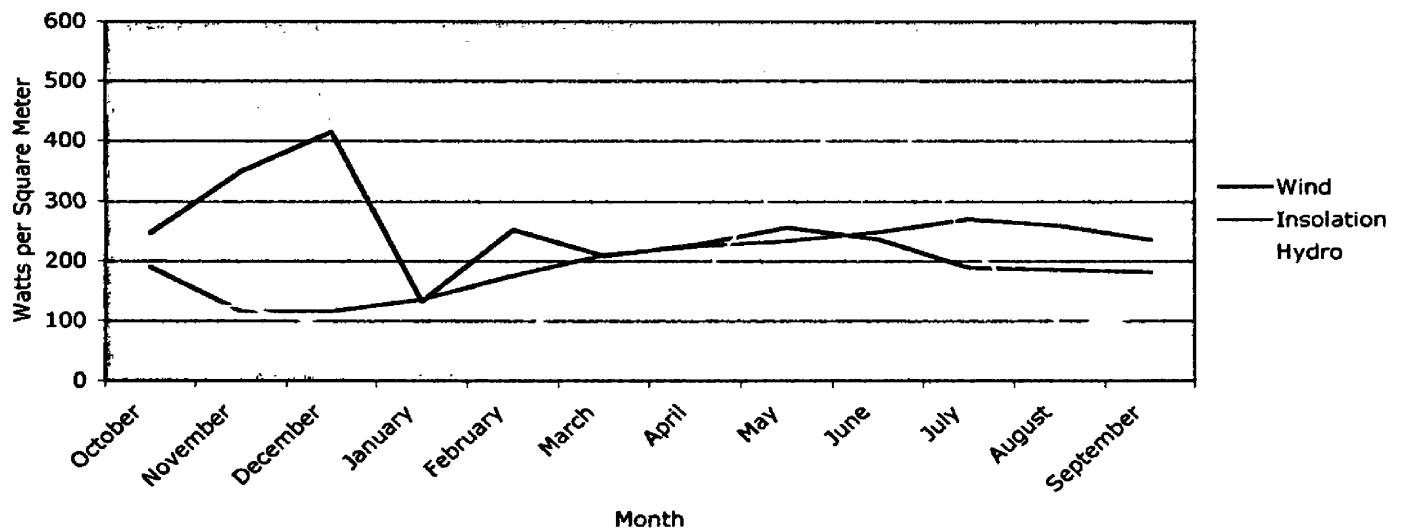


Figure 1. Seasonally Variable Resources for Electricity Generation at 11.92 degrees W, 46.57 degrees N.



## ***Wind***

The energy potential of wind is based upon wind velocity and air density (usually measured as atmospheric pressure), and is generally expressed as wind-power density, in units of watts per square meter ( $\text{W/m}^2$ ). Wind-power density can be calculated, given these two variables, using the equation:  $\text{W/m}^2 = 0.5 * \text{air density in kg/m}^3 * v^3$ .<sup>23</sup>

Wind itself is the result of the uneven heating of the earth's surface, and subsequently of air masses. As warmer, less dense air rises, pressure gradients form near the Earth's surface, and air moves from areas of higher to areas of lower pressure. On the scale of continents, this creates prevailing wind patterns. On a local scale, air movement is affected by topography and surface roughness. In areas of varied topography, the highest wind-power density is usually found on hilltops and ridges. In a given location, wind-power density can be maximized by installing turbines fifty meters or more above the surface to avoid drag from surface roughness. Power density at turbine height must often be estimated from measurements taken near the surface.

## ***Watercourses***

Facilities that capture the kinetic energy of watercourses and convert it into electricity or mechanical work vary both in generation capacity and method of handling water.<sup>24</sup> Though definitions vary, in this study I shall use the term "large-hydro" to refer

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<sup>23</sup> Danish Wind Industry Association, *Wind Energy Reference Manual* (Copenhagen, 2003, accessed 10 September 2003); available from <http://www.windpower.org/en/stat/unitsw.htm>.

<sup>24</sup> U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, "Hydropower" (Washington, D.C.: 2003, accessed December 2003), available from <http://www.eere.energy.gov/RE/hydropower.html>.

to facilities with installed capacity greater than thirty megawatts (MW); “small-hydro” will be used in reference to those facilities between 0.1MW (100kW) and 30 MW, and “micro-hydro” will refer to those with a capacity of less than 0.1 MW. Facilities that store water behind a dam are termed “impoundment” facilities, and are usually large-hydro or small-hydro. A “diversion,” or run-of-the-river, facility channels part of the flow through a generator and may not require a dam. Other facilities pump water to a higher reservoir during times of low demand, and release it through a generator during peak demand, and are termed “pumped storage.” Hydropower is unique in that it is considered both a conventional, large-scale, centralized electric source, as well as a potentially small-scale, renewable energy source. I have included it to highlight watercourses with potential for small- or micro-scale development.

In October of 2003, the Idaho National Engineering and Environmental Laboratory (INEEL) published a draft report detailing the potential for “low head/low power” hydropower resources in the United States.<sup>25</sup> “Low head/low power” hydropower resources are defined as watercourses with less than thirty feet of head and generation potential of less than one MW. In rounded numbers, the report estimates that Montana has a total remaining potential for hydropower development of 3000MW. It further classifies this potential as 775MW of high head/high power, 725MW of low head/high power, 900MW of high head/low power, and 600MW of low head/low power.<sup>26</sup> Of the

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<sup>25</sup> Douglas G. Hall, Shane J. Cherry, Kelly S. Reeves, Randy D. Lee, Gregory R. Carroll, and Garold L. Sommers, *Hydropower Potential of the United States with Emphasis on Low Head/Low Power Resources* (Washington D.C.: United States Department of Energy, 2003), v, DOE/ID-11111.

<sup>26</sup> The report estimates the total potential for Montana at 1777MW, but excludes 280MW in areas where such development is prohibited, resulting in a total of 1497MW available.

hydropower facilities currently in place in Montana totaling 1200MW of installed capacity, most is high head/high power, while the remaining categories total only 11MW. These estimates suggest that there is much remaining potential for hydropower development in Montana, especially in the virtually untapped categories of low head or low power sites. Figure 2 demonstrates the seasonal nature of stream flow, and thus, hydropower potential, greatest in the spring and summer, and peaking around the beginning of June.<sup>27</sup> Also notice the relatively constant flow from November through March.

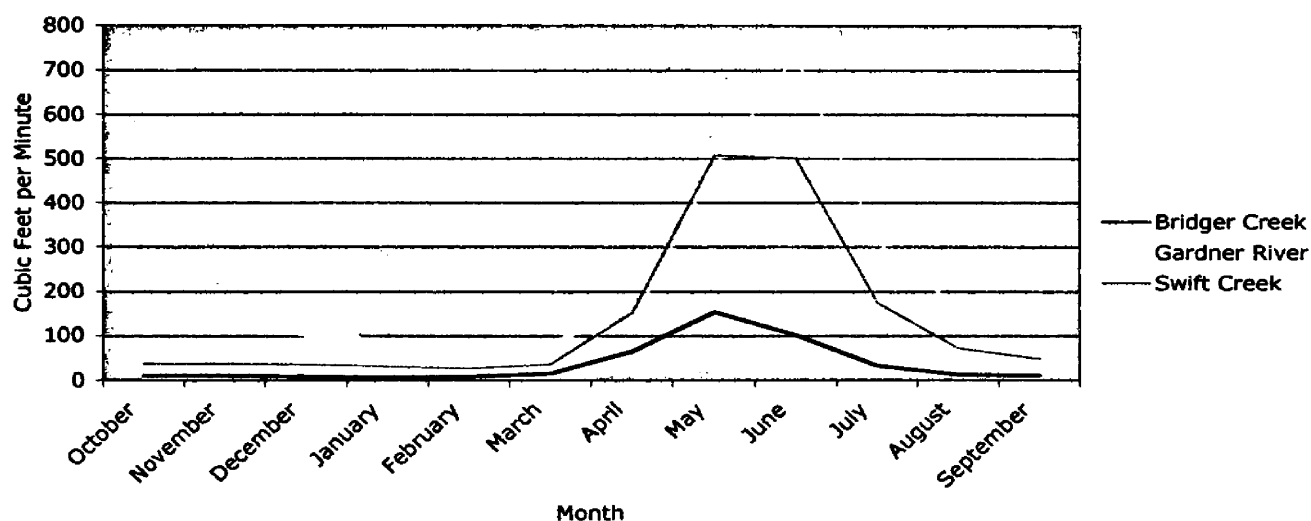


Figure 2. Average monthly watercourse flow.

The Low Impact Hydropower Institute has established criteria by which hydropower facilities can be certified “low impact,” meaning that the impact of the facility upon the environment has been minimized. These criteria address several issues

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<sup>27</sup> Sites randomly selected from the USGS stream gauge data. Montana State Library, Natural Resource Information System, *Montana USGS Stream Flow Stations* (Helena: 2003), accessed April 2003, available from <http://nris.state.mt.us/nsdi/nris/hd42.html>.

including: dewatering, change in flow seasonality, water quality, fish passage and protection, watershed protection, wildlife, and cultural resources.<sup>28</sup> Designing a facility that meets these criteria at a given site will require extensive site-specific research and is beyond the scope of this study. I intend to provide the basic foundational data that will suggest the possibility of such development, rather than analyzing the commercial development potential of any given site. The latter site-specific analysis can only be undertaken by a potential developer.

### *Solar*

The variation in insolation throughout the year is the cause of seasonality, rather than a result. The earth spins on an axis tilted at 23.5 degrees relative to the plane of its orbit around the sun. When the north axis is tilted toward the sun, the northern hemisphere receives longer periods of insolation. At forty-five degrees north latitude – a parallel that passes through Montana – there are more than fifteen hours between sunrise and sunset in June, but less than nine hours in December. In addition to shorter periods of daylight, winter months receive solar radiation at a lower angle, further reducing insolation per square meter of surface area due to increased reflection, absorption, and refraction in the atmosphere. Insolation is also the origin of wind, watercourse, and biomass energy. Uneven surface heating creates air masses with differing temperature and moisture characteristics. The expansion of warm air and movement of air from areas of higher to areas of lower pressure creates wind. Rain, the seasonally variable source of

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<sup>28</sup> Low Impact Hydropower Institute, “Criteria Summary” (Portland, ME, 2003, accessed December 2003), available from [http://www.lowimpacthydro.org/criteria\\_summary\\_01\\_03.pdf](http://www.lowimpacthydro.org/criteria_summary_01_03.pdf).

water in rivers and streams, is another product of the movement, heating and cooling of these air masses.<sup>29</sup> Insolation is the energy used by vegetation for growth, and is the basis for biomass energy.

### ***Geothermal***

Heat energy from the earth's core is, in some locations, transported to the surface by the circulation of groundwater, and can be utilized for heating or electricity generation.<sup>30</sup> Geothermal energy is used throughout the world, most notably in places like Iceland and New Zealand, but also in Montana. The mountainous western portion of the state has many geothermal hot springs, while eastern Montana is known to have deep aquifers of hot water that must be accessed through drilling.<sup>31</sup>

Notable geothermal projects in Montana include greenhouse heating at Chico Hot Springs; building and water heating at White Sulphur Springs and Fairmont Hot Springs.<sup>32</sup> On a grander scale, in New Zealand, the Mokai Geothermal Power Plant, owned by the indigenous Maori people, is currently being expanded from sixty to 100 megawatt capacity.<sup>33</sup> In Iceland, where sixty-six percent of the electricity is generated by

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<sup>29</sup> As air rises and cools (the result of heating at the surface, interaction with a more dense air mass, or movement over mountains), its water capacity is reduced, eventually resulting in precipitation.

<sup>30</sup> U.S. Department of Energy, Geothermal Technologies Program, *Geothermal Basics Overview* (Washington D. C.: 2004, accessed April 2004); available from <http://www.eere.energy.gov/geothermal/overview.html>

<sup>31</sup> National Center for Appropriate Technology, Montana Green Power, *Geothermal Resources* (Butte: 2004, accessed April 2004); available from <http://www.montanagreenpower.com/index.html>.

<sup>32</sup> Ibid.

<sup>33</sup> "Mokai Geothermal Power Plant, New Zealand" (London: Power Technology, accessed April 2004); available from <http://www.power-technology.com/projects/mokai/>.

hydroelectric or geothermal plants, the Nesjaveller Geothermal Plant cogenerates sixty megawatts of electricity, as well as providing hot water.<sup>34</sup>

Despite the many advantages of geothermal power, much of Montana is arid, and water is scarce. Removing groundwater through geothermal development could lower aquifer levels. To address this concern, many geothermal facilities pump spent geothermal water back into the ground.

### ***Biomass***

The use of biomass for energy dates back to the controlled use of fire, and is still an important fuel around the world. Biomass can be used with minimal technology, can be stored and transported, and is often cheaply available to local populations. Though the use of biomass releases carbon dioxide, a greenhouse gas, into the atmosphere, the cycle of vegetation absorbing carbon dioxide for growth balances the release if the biomass is harvested in a sustainable manner, and results in a net zero change in atmospheric carbon dioxide levels. Additionally, burning methane from livestock waste and landfill gas converts it into carbon dioxide, which has a 100 year greenhouse-gas potential twenty-one times less than that of methane.<sup>35</sup>

In terms of more modern technology, biomass has an advantage over other renewable resources because it can be converted into high-quality liquid fuel such as

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<sup>34</sup> Orkuveita Reykjavíkur “Nesjaveller Power Plant” (Reykjavík, Iceland: accessed April 2004); <http://www.or.is/Forsida/ENGLISHVERSION/SITESENVIRONMENT/Nesjavellir/NesjavellirPowerPlant/view.aspx?>

<sup>35</sup> U.S. Environmental Protection Agency, Office of Atmospheric Programs, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2000* (Washington D.C.: April 2002); EPA 430-R-02-003, available from [www.epa.gov/globalwarming/publications/emissions](http://www.epa.gov/globalwarming/publications/emissions).

ethanol or biodiesel and used in transportation applications. Biomass is also often used in coal-fired power plants to reduce emissions of certain pollutants, and can produce heat and electricity simultaneously in cogeneration scenarios.

In reality, the availability of biomass resources is seasonal. According to Department of Agriculture statistics, over the past five years (1999 – 2003) there were an average of 1.4 times as many cattle in Montana in July as there were in January.<sup>36</sup> Calves are born in the spring, and livestock are shipped out of state or slaughtered in the fall.<sup>37</sup> The rate at which gas is produced in landfills is a function of both moisture and temperature, attributes that change seasonally. Forest residues are available when loggers and mills are operating; which may be more closely related to economy than season. Biomass, however, is a unique case in this study since these resources are easily stored in their raw form, or when digested to a higher quality medium such as methane or ethanol. In this study, therefore, I considered biomass resources as being constant throughout the year, and do not account for fluctuation in availability by season.

### Similar Studies

Four recent studies have focused upon similar goals. Two reports published in 2002 attempted to quantify renewable resources in Montana as part of larger regional studies. The *Renewable Energy Atlas of the West* considers wind, geothermal, biomass,

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<sup>36</sup> U.S. Department of Agriculture, National Agricultural Statistics Service, *Cattle* (Washington D.C.: 2004); available from <http://usda.mannlib.cornell.edu/reports/nassr/livestock/pct-bb/>.

<sup>37</sup> Thomas Chard II, Montana Agricultural Statistics Office, personal communication, October 2003.

and solar potential.<sup>38</sup> The Tellus Institute report; *Clean Electricity Options for the Pacific Northwest*, considers wind, geothermal and biomass, as well as conservation potential.<sup>39</sup> Neither addresses the potential of mini-hydro installation, and both suggest that additional refinement of resource distribution will be necessary for informed planning.<sup>40</sup> The University of Victoria completed a small-scale quantification of solar, wind, and tidal energy potential for Race Rocks, British Columbia, with the specific goal of making the navigational beacon on the remote archipelago self-sufficient.<sup>41</sup> A dissertation written by Deborah Feder, and published by The Pennsylvania State University in 2001 quantified the energy resource potential of wind, watercourses, and insolation, as well as the nature of end-use demand, for three case study sites in Pennsylvania. This study will focus upon the state of Montana, a mid-scale among these four studies, and will consider wind, insolation, geothermal, watercourse, and biomass energy potential.

### Purpose Statement

The purpose of this thesis is to display and evaluate the seasonal distribution of insolation, wind, watercourse, geothermal, and biomass energy resources across Montana, suggest opportunities for these resources to form complements in electric and heat distributed-generation scenarios, and to provide this information to policy-makers and local communities that desire to minimize dependence upon the national energy grid,

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<sup>38</sup> Nielsen and others, *Renewable Energy Atlas*, *passim*.

<sup>39</sup> Michael Lazarus, David von Hippel, and Stephen Bernow, *Clean Electricity Options for the Pacific Northwest: An Assessment of Efficiency and Renewable Potentials through the Year 2020* (Boston: Tellus Institute, 2002), *passim*.

<sup>40</sup> Nielsen and others, *Renewable Energy Atlas*, 6; Lazarus, *Clean Energy Options*, 49.

<sup>41</sup> T. Niet and G. McLean, "Race Rocks Sustainable Energy System Development," in *Proceedings of the 11<sup>th</sup> Canadian Hydrogen Conference held in Victoria 17-21 June 2001*, *passim*.



improve the security of their energy sources, and minimize their impact upon the environment.

The quality of data available for each resource varies widely, and while I am using the most accurate and comprehensive data available to me, the end product will be more useful for highlighting patterns in the landscape than for depicting exact quantities and potential.

This thesis will address basic geographical questions of “where?”, “what?” and “how much?”. It will contribute to the discussion of geographical questions including: “What makes places and landscapes different from one another and why is this important?”<sup>42</sup>

Readers should be advised that I do not mean to suggest this entire resource potential is simultaneously available. Utilizing resources in one location may reduce resource potential in adjacent locations. I mean only to provide a snapshot profile of potential, and suggest that resources used in concert are more continuous and have greater potential than those used alone. Additionally, not all locations mapped are suitable for development. Suitability is dependent upon many factors unrelated to the actual resource potential, including land ownership, proximity to demand or transmission lines, and ecological sensitivity. These, and other site factors, should be evaluated on a case-by-case basis.

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<sup>42</sup> Reginald G. Golledge, “The Nature of Geographic Knowledge,” *Annals* 92, no. 1 (2002): 9; Susan Cutter Reginald G. Golledge, and William L. Graf, “The Big Questions in Geography,” *The Professional Geographer* 54, no. 3 (2002): 307; *ibid*, 314.

## CHAPTER THREE

### METHODS

#### Study Area

The administrative boundary of the state of Montana is the geographical extent of this study. Given that energy policy-making and regulation happen at the state level, it will be advantageous to consider conditions continuously across this area for purposes of comparability.

#### Data

Typical of a regional geography study, this inquiry covers several separate data layers, including energy-resource potential (in both Btu and MWh, assuming 25% conversion efficiency) for wind, watercourses, insolation, geothermal, and biomass. Data sources were chosen for each resource separately. Data for resources that are conducive to heating applications will be aggregated separately from resources that are conducive to electricity generation. Note that there will be significant overlap in these tallies. Insolation, geothermal, and biomass resources are conducive to both heating and electricity generation, and will be counted in both. The resources can be used in either application, or some combination that does not exceed the total. Heating resources will be tallied in British thermal units per hour per square meter ( $\text{Btu/h/m}^2$ ), while electricity resources will be tallied in watts per square meter ( $\text{W/m}^2$ ). Measuring in power density

units is more appropriate for some resources than for others. For example, solar and wind resources are distributed across the landscape and are conducive to analysis using power density, while hydropower is highly concentrated in watercourses, and more appropriately analyzed as point or line data. To compare resources across the state, however, all have been converted into power density.

### ***Wind***

Four hundred meter grid resolution annual wind data, developed by TrueWind Solutions (TWS), is available in raster format on the Montana Natural Resources Information System (NRIS) web site.<sup>43</sup> This is the most accurate wind data available, and is used in both the *Renewable Energy Atlas of the West*, and *Clean Energy Options for the Pacific Northwest*.<sup>44</sup>

Monthly wind-power density estimates are not yet available. To create monthly estimates, I obtained monthly wind-power density measurements in watts per square meter ( $\text{W/m}^2$ ) for 54 sites in Montana from the Montana Wind Energy Atlas.<sup>45</sup> Data in the Atlas was collected by various entities including the National Weather Service, Federal Aviation Administration, the U.S. Air Force, Montana Department of Health and Environmental Sciences' Air Quality Bureau, U.S. Environmental Protection Agency, U.S. Bureau of Reclamation, Montana Department of Natural Resources and

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<sup>43</sup> Montana State Library, Natural Resource Information Service, *Wind GIS Data* (Helena: 2003, accessed April 2003); available from <http://nris.state.mt.us/nsdi/nris/windpower.html>.

<sup>44</sup> Lazarus, von Hippel, and Bernow, *Clean Energy Options*, 36; Nielsen and others, *Renewable Energy Atlas*, metadata.

<sup>45</sup> GeoResearch, Inc., *Montana Wind Energy Atlas* (Helena: Montana Department of Natural Resources and Conservation, 1987), *passim*.

Conservation, U.S. Department of Energy, Bonneville Power Administration, Western Area Power Administration, U.S. Forest Service, and private companies.<sup>46</sup> Each of these entities collected wind data in its own way, for its own purposes, and during different time periods. Sites were monitored for as long as nineteen years, and as short as less than one year; none more recent than 1987. Data recovery ranged from poor to excellent. Some sites are representative of large geographical areas, while others are representative of only a small site - as in the case of a hilltop or ridge. The atlas contains notes describing the characteristics of each site. Additionally, the height of the instrument monitoring the wind was variable, and always significantly lower than modern wind turbines are mounted. This variability in data quality should be considered when reviewing monthly wind-power estimates. The general theme – that Montana winds are strongest in the winter, and weakest in the summer – is communicated by the data despite these imperfections.

I estimated wind-power for each month by calculating for each site the ratio of average wind-power density for each month to the annual average wind-power density at that site, then interpolating the monthly deviation point data to raster, and multiplying the deviation ratios by the annual TrueWind Solutions data. For example, the data collected at “Great Falls NWS Airport” shows a yearly average wind-power density, collected at 6.7 meters, of 183 W/m<sup>2</sup> and a January average wind-power density at that site was 298 W/m<sup>2</sup>. The ratio for January at this location is  $298 \text{ W/m}^2 / 183 \text{ W/m}^2 = 1.63$ . I calculated this ratio for all site/month combinations, and used the ratio values to interpolate from

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<sup>46</sup> Ibid, 3.

points to raster using an inverse distance weighted method. Ideally, wind-power density estimates would first be extrapolated to fifty meters above the surface for each monitoring station, and then these values would be used to create the deviation raster. This could be done by first extrapolating wind-velocity values to meters, and then converting the velocity estimates into power-density estimates. Unfortunately, the data for daily wind-velocity readings is only available on paper, and would require entry into a spreadsheet to be used in calculations. This is a prohibitive amount of work that I will leave to a more worthy data-entry person. Alternatively, I used a slightly less-ideal method of creating the deviation rasters. I assumed the ratio of average monthly wind-power density to average yearly wind-power density is the same at the anemometer height and at fifty meters for a given site. Therefore, I did not extrapolate the values to fifty meters, but rather calculated the ratios of monthly average wind-power density to yearly average wind-power density at the given anemometer height, assuming this is a reasonable estimate of the ratio at fifty meters. I used the Spatial Analyst raster calculator to multiply the ratios for each with the TrueWind Solutions annual data. The resulting grids contain wind-power density estimates for each month.

### ***Watercourses***

The potential for development of small/mini-hydro and micro-hydro in Montana was been evaluated by the Idaho National Energy and Environmental Laboratory (INEEL) for the DOE, and published in an October 2003 draft report.<sup>47</sup> INEEL used a

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<sup>47</sup> Douglas G. Hall, Shane J. Cherry, Kelly S. Reeves, Randy D. Lee, Gregory R. Carroll, and Garold L. Sommers, *Hydropower Potential of the United States with Emphasis on Low Head/Low Power Resources* (Washington D.C., United States Department of Energy, 2003).

digital elevation model (DEM) to locate catchments and theoretical streams.<sup>48</sup>

Theoretical stream locations were checked against the National Hydrography Dataset, and segments that were not present in the National Hydrography Dataset were removed from the study. To calculate ideal power potential for a stream reach, the total change in elevation for the reach and flow rates at both ends were used in the equation:

$$\text{Power (kW)} = \kappa[Q_i * H + (Q_o - Q_i) * H/2]$$

$$\kappa = (1/11.8)$$

$Q_i$  = flow rate at upstream end of reach in feet<sup>3</sup>/second

$Q_o$  = flow rate at downstream end of reach in feet<sup>3</sup>/second

$H = z_i - z_o$ , hydraulic head in feet

$z_i$  = elevation at upstream end of reach in feet

$z_o$  = elevation at downstream end of reach in feet

Since this equation uses actual stream flow as measured at gauge stations, rather than theoretical flow, viscous losses resulting from travel over rough stream beds are accounted for.

It is important to distinguish between ideal power-generation potential – the potential estimated by these equations – and plant capacity (the actual power generation of a specific hydroelectric plant operating at maximum capacity).<sup>49</sup> For example, a watercourse with an annual average estimated power potential of eight kilowatts may have a hydroelectric plant installed with a capacity of twelve kilowatts to take advantage

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<sup>48</sup> Ibid, 6-10.

<sup>49</sup> Douglas G. Hall, Idaho National Engineering and Environmental Laboratory, personal communication, March 2004.

of higher seasonal flows. The plant factor is the ratio of actual power generation to maximum plant capacity. On average, plants in the United States have a plant factor of one half.<sup>50</sup> In the example above, the plant has been sized to take advantage of seasonal flows, and may produce twelve kilowatts of electricity in the spring, but the yearly average will be much less than that, likely six kilowatts, because of seasonally low flows and plant inefficiencies. The estimates given in this study do not assume efficiency losses, which are specific to the technology used for power generation. When developing hydropower resources, it is critical to account for these losses to provide a realistic estimate of expected power output.

Given that the seasonal variation in hydropower potential is due solely to the fluctuation in flow variable, I estimated monthly hydropower potential using several years of USGS gauge station flow data and the same method outlined for estimating monthly wind-power potential. I calculated monthly deviation from average ratios for each gauge station by dividing the annual average flow by the monthly average flow, interpolate to raster from these points for each month. I converted INEEL's annual estimate line data into raster data based upon the 400 meter resolution TrueWind Solutions wind density cell size. This distributed the watercourse energy potential estimates across the area immediately adjacent to the waterway centerline, within a maximum of 566 meters.<sup>51</sup> This approach has the potential to distort the waterway shape, and increase the granularity of the data, but given the scale of the maps in this study,

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<sup>50</sup> Ibid.

<sup>51</sup> If the segment passes through the corner of a raster cell, the distance from the center line to the farthest cell corner will be the length of the hypotenuse of a right triangle, described by the Pythagorean theorem,  $\sqrt{(400\text{m}^2 + 400\text{m}^2)} = 566\text{m}$ .

changes of a few hundred meters are considered minimal and acceptable. Each cell will contain the hydropower potential estimate for the segment in watts per square meter. The hydropower potential estimate was divided by the segment length, and that value assigned to each cell in the segment. For example, if a segment is 1000 meters long, and has a hydropower potential of 100 kilowatts (100,000 watts), the cell value will be equal to 100,000 watts/1000 meters, or 100 watts per meter. For comparison with other resources, I will assume that watercourse energy exists within a one meter centerline of the waterway. The segment potential divided by segment length will calculate watts per square meter at the centerline. To produce monthly estimates, these annual estimates will be adjusted by multiplying the annual estimate raster with monthly deviation rasters. Because the cell size is actually 400 meters square, this is a particularly artificial method of estimation, but the concession is necessary to form comparisons with other resources. Given the scale of the final product, this distortion should be minimal, but is important to consider when evaluating the results.

### ***Insolation***

Raster data of insolation is available from the National Renewable Energy Laboratory (NREL) web site in a 40km grid.<sup>52</sup> This grid has attributes for both annual and monthly insolation averages in kilowatt-hours per square meter (kWh/m<sup>2</sup>), and

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<sup>52</sup> “Modeled estimates of monthly average daily total direct normal solar radiation are derived from satellite and/or surface observations, which include cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure, and ozone sampled at a 40-km resolution”. U.S. Department of Energy, National Renewable Energy Laboratory, *Solar Maps* (Boulder, CO: 2003, accessed May 2004); available from [http://www.nrel.gov/gis/solar\\_maps.html](http://www.nrel.gov/gis/solar_maps.html); U.S. Department of Energy, National Renewable Energy Laboratory, *Solar Radiation Resource Information* (Boulder, CO: Renewable Resource Data Center, 2003, accessed April 2003); available from <http://rredc.nrel.gov/solar/>.



estimates the resource available to a flat-plate collector oriented toward the south at an angle equal to the latitude of the location.

Insolation equations:

$$W/m^2 = kWh/m^2day * 1000W/kW * day/24h$$

$$Btu/h/m^2 = W/m^2 * 3.41$$

### ***Geothermal***

Geothermal heat flow data is available from the Southern Methodist University Geothermal Laboratory (SMUGL).<sup>53</sup> Since geothermal energy originates as heat in the molten core of the earth, it is not seasonally variable as many of the other resources are. Since this heat is transmitted to the surface through groundwater, the availability may, however, be affected by drought which can lower the water table. Data used for this study is current as of November, 2003, though there has been little exploratory drilling for geothermal resources in the past two decades.<sup>54</sup>

SMUGL has also modeled Montana's potential for geothermal development based upon heat flow, but accounting for additional factors such as proximity to areas of end use and environmental sensitivity.<sup>55</sup> Unfortunately this geothermal potential data is not expressed in units, and cannot be converted into units to allow comparison with other data sources (Btu and MWh), and consequently, is not useable for my purposes.

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<sup>53</sup> Southern Methodist University, Geothermal Laboratory, *Western Geothermal Area Data Base* (Dallas: 1999, accessed April 2003); available from <http://www.smu.edu/geothermal/georesou/mont.htm>.

<sup>54</sup> Lazarus, von Hippel, and Bernow, *Clean Energy Options*, 44.

<sup>55</sup> Maria Richards, Southern Methodist University Geothermal Laboratory, personal communication, September 2003.

Geothermal data was received from SMUGL as a Surfer \*.dat file with three coordinates for each cell; x and y are spherical coordinates latitude and longitude respectively, and z is the floating-point attribute containing a measure of heat flow to seven decimal places. Conversion to grid in ArcGIS requires integer data, and will lose all decimal places, resulting in an unnecessary loss of precision. To minimize this loss, I used Excel to multiply the heat flow values by 100,000, exported the data as a DBASE IV file, added it to ArcGIS as XY data and exported the data as a point shapefile. Using Spatial Analyst, I interpolated the points to raster with a cell size matching the 400 meter grid TrueWind Solutions data using the inverse distance weighted method, and all defaults except a cell size of 0.0833333, and heat flow as z. I then converted the raster into polygons with Spatial Analyst, and divided heat flow by 100,000 to restore the original values. Using this method, I maintained five of seven original decimal places. This is the maximum precision possible using this method, since the conversion from floating point to integer does not read more than eight digits, and some heat flow values have three digits before the decimal. This loss of precision is minimal and acceptable considering the much lower precision of other data sets.

### ***Biomass***

The biomass category includes landfill gas and resources that have recently been converted from solar energy to a carbon-based energy through vegetation, including crop residues, animal waste, and forest residues.

Data for landfill gas is available from the Environmental Protection Agency's (EPA) Landfill Methane Outreach Program (LMOP) web site, and from the Montana

Department of Environmental Quality.<sup>56</sup> The LMOP considers landfills with waste in place (WIP) of at least 1,000,000 tons that are operational, or have closed since 1993.<sup>57</sup> In Montana five landfills meet this criteria and are considered potential landfill gas-to-energy projects. There are, however, many smaller landfills in Montana, and the potential for these to generate energy is not captured under these criteria. These smaller landfills could still work in local niche applications, such as heating buildings or greenhouses.<sup>58</sup> Data from the Montana Department of Environmental Quality includes small landfills, and was be used to estimate that potential. Landfills with less than 1,000,000 tons of WIP that are closed were not considered, as they are exceedingly small and remote.<sup>59</sup>

The equation used for gas production given in tons of WIP may overestimate the rate at which Montana landfills produce gas. Montana's dry, cold climate slows the process of gas production, distributing it over a longer period of time. Also, since landfill gas production decreases over time after the landfill is closed, the power potential calculated for these landfills is time-sensitive.

Landfill methane equations:

Assume 1 ton = 1.667 cubic yards

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<sup>56</sup> U.S. Environmental Protection Agency, Landfill Methane Outreach Program, *Landfill Methane Data* (Washington, D.C., 2003, accessed April 2003); available from <http://www.epa.gov/lmop/projects/projects.htm>; Montana Department of Environmental Quality, "Tonnage for All Class II, III, and IV Landfills", *Landfill Database* (Helena, Montana: 2004).

<sup>57</sup> Diana Pape, Elizabeth O'Niel and Jennifer Kish, *Landfill Gas-to-Energy Project Opportunities: Background Information on Lanfill Profiles* (Washington D.C.: ICF Inc. for the U.S. Environmental Protection Agency, 1999), 2-2, EPA 430-K-99-002.

<sup>58</sup> Ibid.

<sup>59</sup> Ricknold Thompson, Montana Department of Environmental Quality, Solid Waste Program, personal communication, 29 October 2003.

watts = estimated methane generation (million standard cubic feet (mmscf)/day)\* gas collection efficiency (.075) \* (1000 Btu / scf) \* (10<sup>6</sup> scf/mmscf) \* (1 Wh/1000 Btu) \* (1 day/24hours)

Btu per hour = estimated methane generation (mmscf/day) \* gas collection efficiency (0.75) \* (mmBtu/10<sup>6</sup> Btu) \* (10<sup>8</sup> Btu/mmscf) \* (1 day/24hours)

MWh per year = estimated methane generation (mmscf/day) \* gas collection efficiency (.075) \* (1000 Btu/scf) \* (10<sup>6</sup> scf/mmscf) \* (1 MWh/10<sup>6</sup> Btu) \* (365 days/year)<sup>60</sup>

Btu per year = estimated methane generation (mmscf/day) \* gas collection efficiency (0.75) \* (mmBtu/10<sup>6</sup> Btu) \* (10<sup>8</sup> Btu/mmscf) \* (365 days/year)

Estimated CO generation (mmscf/day): if WIP < 907,200 tons = 0.05085 \* (6.95x10<sup>-6</sup> \* WIP<sub>m</sub> (tons))

if WIP ≥ 907,200 tons = 0.05085 \* (8.22 + (5.03x10<sup>-6</sup> \* WIP<sub>m</sub> (tons)))

WIP<sub>m</sub> (tons) = (WIP (tons)/(year<sub>current</sub> - year<sub>open</sub>)) \* (# of years open in the last 30 years)<sup>61</sup>

Crop residue and animal waste data was obtained from the USDA Published Estimates database web site.<sup>62</sup> Counties are the spatial unit in both data sets. Crop harvest data was obtained for barley, corn, and wheat. The following equations and constants were used for calculating Btu and MWh potential for one year.<sup>63</sup>

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<sup>60</sup> Equations for Btu and MWh estimates are adapted from Pape, *Landfill Gas-to-Energy Project Opportunities*, 3-6.

<sup>61</sup> It is assumed that methane is emitted from waste for 30 years after disposal.

<sup>62</sup> U.S. Department of Agriculture, National Agricultural Statistics Service, "Crops County and District Data" in *Published Estimates Database* (Washington, D.C., 2003, accessed November, 2003); "Livestock County Data" in *Published Estimates Database* [database on-line] (Washington, D.C., USDA National Agricultural Statistics Service, 2003, accessed November, 2003).

<sup>63</sup> All livestock and crop residue equations and definitions paraphrased from the *Renewable Energy Atlas of the West*; Nielsen, *Renewable Energy Atlas*, 76.

Although seasonality is not as critical for biomass resources, given their ease of storage, there is seasonal fluctuation in the amount of biomass becoming available at a given time. The majority of crops are harvested in the fall, and there are significantly more animals in the state between July and October.

Crops equations (given bushels or tons):

$$\text{MWh} = (\text{bushels} * \text{lbs per bushel} * \text{residue fraction} * \text{energy density} * \text{residue factor} * \text{moisture factor}) / (2000 * \text{energy transfer factor} * 1000)$$
$$\text{Btu} = (\text{bushels} * \text{lbs per bushel} * \text{residue fraction} * \text{energy density} * \text{residue factor} * \text{moisture factor}) / (2000 * 1000)$$
$$\text{MWh} = (\text{tons} * \text{residue fraction} * \text{energy density} * \text{residue factor} * \text{moisture factor}) / (\text{energy transfer factor} * 1000)$$
$$\text{Btu} = (\text{tons} * \text{residue fraction} * \text{energy density} * \text{residue factor} * \text{moisture factor}) / 1000$$

Crops Definitions:

Bushels: bushels of grain harvested

Lbs per bushel: weight of an average bushel in pounds (barley: 48, corn: 56, wheat: 60)

Residue fraction: assumed fraction of residue that can be taken from fields without negatively affecting soil quality (0.3 for all grains)<sup>64</sup>

Energy density: energy contained in one ton of dry residue ( $15 * 10^6$  BTUs)<sup>65</sup>

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<sup>64</sup> This fraction may be higher in high yield years. James D. Kerstetter and John Kim Lyons, *Logging and Agricultural Residue Supply Curves for the Pacific Northwest* (Pullman: Washington State University Energy Program for the United States Department of Energy, 2001); contract # DE-FC01-99EE50616, 32.

<sup>65</sup> Supported by Oak Ridge National Laboratory bioenergy conversion factor of 7300 Btus per pound for dry agricultural residues. Oak Ridge National Laboratory, *Bioenergy Conversion Factors* (Oak

Residue factor: units of available residue for every unit of grain harvested (barley: 1.5, corn: 1.0, winter wheat: 1.7, spring/durum wheat, 1.3)

Moisture factor: ratio of dry weight to residue weight (barley: 0.9, corn: 1.0, wheat: 0.87)

Energy transfer factor: conversion efficiency of heat to electrical energy (assumed 25% efficient: 13,600kWh/BTU)

Livestock data was obtained from the National Agricultural Statistics Service database.<sup>66</sup> Cattle and sheep data is from the 2003 January inventory, while hog data is from the 2002 January inventory.

Livestock equations (given number of animals):

Watts = (animals \* volatile solids \* volume \* energy per volume \* (1-handling loss) \* digester efficiency) \* (1/ energy transfer factor) \* (1 day/24 hours)

Btu/hour = (animals \* volatile solids \* volume \* energy per volume \* (1-handling loss) \* digester efficiency) \* (1 day/24 hours)

Livestock definitions:

Animals: number of animals

Volatile solids: weight of volatile solids produced by an animal in pounds per day (beef cattle: 6.0, dairy cattle: 11.2, swine: 1.2, sheep: 0.92)

Volume: volume of gas generated in cubic feet per pound (beef cattle: 9.76, dairy cattle and sheep: 14.0, swine: 8.0)

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Ridge: United States Department of Energy, 2004, accessed 31 May 2004); available from [http://bioenergy.ornl.gov/papers/misc/energy\\_conv.html](http://bioenergy.ornl.gov/papers/misc/energy_conv.html).

<sup>66</sup> U.S. Department of Agriculture, National Agricultural Statistics Service, QuickStats, *Livestock Data* (Washington D.C.: United States Department of Agriculture, 2004); available from <http://www.nass.usda.gov:81/ipedb/>.

Energy per volume: BTUs per cubic foot of gas ( beef cattle, dairy cattle, and sheep: 600, swine: 650)

Handling loss: expected waste management handling loss (beef cattle and sheep: 0.25, dairy cattle: 0.10, swine: 0.20)

Digester efficiency: expected efficiency of digester (beef cattle and swine: 0.50, dairy cattle and sheep: 0.35)

Energy transfer factor: conversion efficiency of heat to electrical energy (assumed 25% efficient: 13.6Btu/Watt hour)

365: constant for converting energy per day to energy per year.

Forest residue data was obtained from the USFS Forest Inventory and Analysis Timber Product Output database.<sup>67</sup> I have included mill residues (residues not used in the milling process) and logging residues (woody material dead or downed by the logging process, but not used for traditional forest products). Data for logging residues is available in cubic feet of green woody material, while mill residue data is available in tons of dry woody material. The conversion to available energy is based upon several assumptions, including the weight of green logging residues per cubic foot and energy per ton of material based upon moisture content. When calculating the energy potential of mill residues, I assumed the residues would be dry – as they are given in the database. When calculating the energy potential of logging residues, however, I converted the

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<sup>67</sup> U.S. Forest Service, "Forest Residue Data", *Forest Inventory and Analysis Data Base* (Washington, D.C: United States Forest Service, 1989, accessed January 2004), available from [http://ncrs2.fs.fed.us/4801/fiadb/rpa\\_tpo/wc\\_rpa\\_tpo.ASP](http://ncrs2.fs.fed.us/4801/fiadb/rpa_tpo/wc_rpa_tpo.ASP).

weight from green tons to air dry tons. This method incorporates the assumption that at the time of use, logging residues will likely be air-dried, but not kiln dried.

The nature of resource distribution differs between mill and logging residues. Mill waste is conveniently concentrated at the mill location, reducing transportation costs, but 98% is already used for fuel or fiber (much of it fuels the mill itself).<sup>68</sup> Logging residues are distributed across large areas, and require transportation to an energy generation facility. Additionally, much forest waste must be left in place to maintain ecological values.<sup>69</sup> I have assumed that 100% of mill residue is available for use as fuel, and since an estimated 98% is currently used, the remaining 2% is included in these forest resource calculations. I have assumed 20% of logging residue is potentially available for use as fuel and will leave enough residue in place to maintain ecological function.<sup>70</sup> The percentage of logging residue that could be cost-effectively used for energy generation is dependent upon proximity generation facilities, cost of transportation, incentive programs, and fuel prices. I have made no assumptions about these factors, which would likely further limit the amount of usable resource.

Forest residue equations:

$$\text{Mill W/m}^2 = (1 \text{ Watt}/13.6\text{Btu} * 1,000,000\text{Btu}/\text{Mbtu} * 17\text{Mbtu}/\text{dry ton woody material} * \text{dry tons mill residues}) / \text{county area in square meters}.$$

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<sup>68</sup> Tony G. Johnson, ed., *United States Timber Industry – An Assessment of Timber Product Output and Use, 1996* (Washington D.C.: United States Forest Service, 1996), v.

<sup>69</sup> Ibid.

<sup>70</sup> Ibid.



Mill Btu/m<sup>2</sup> = (1,000,000Btu/Mbtu \* 17Mbtu/dry ton woody material \* dry tons mill residues)/ county area in square meters.

Logging W/m<sup>2</sup> = (1 Watt/13.6Btu \* 1,000,000Btu/Mbtu \* .623 \* 14 Mbtu/ air dry ton woody material \* cubic feet green logging residues \* lbs/cubic foot green logging residues)/ county area in square meters.

Logging Btu/m<sup>2</sup> = (1,000,000Btu/Mbtu \* .623 \* 17 Mbtu/green ton woody material \* green tons logging residues)/ county area in square meters.

Forest residue definitions:

Density of green woody material: 46.5 lbs/cubic foot for softwood, 53.2 lbs/cubic foot for hardwood.<sup>71</sup>

Wet-basis moisture content: green: 45.4%,<sup>72</sup> air dry: 12.5%<sup>73</sup>, dry: 0%

Energy yield: 17 Mbtu/dry ton woody material, 14 Mbtu/air dry ton woody material<sup>74</sup>

Residue weight: 0.0175 tons/cubic foot woody material.

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<sup>71</sup> Haq gives the Forest Service weight per volume standards for air-dry (12-13% wet basis moisture content) woody material. I converted to green by dividing weight by cubic feet and multiplying by 100 + the difference in moisture content by percent using 45.4% wet basis moisture content for green woody material. Zia Haq, *Biomass for Electricity Generation* (Washington D.C.: United States Department of Energy, Energy Information Administration, 2002, accessed February 2004), table 21; available from <http://www.eia.doe.gov/oiaf/analysispaper/biomass/table3.html>.

<sup>72</sup> Weighted average of species groups. W. Brad Smith, *Assessing Removals for North Central Forest Inventories* (Washington D.C.: United States Department of Agriculture Forest Service, 1991), C-4, NC-299.

<sup>73</sup> Zia Haq, *Biomass for Electricity Generation*, table 21.

<sup>74</sup> The dry woody material estimate is from Lazarus, 2002, and is supported by an estimate of 17.2 million Btus per dry ton used by Haq for the Energy Information Administration. The green woody material estimate is from the Energy Information Administration 1996 *Renewable Energy Annual*. Data for mill residues are in dry tons, while logging residues are in green tons (per personal communication with Brad Smith). Lazarus, von Hippel, and Bernow, *Clean Energy Options*, A-5; Haq, *Biomass for Electricity Generation*, table 21; United States Department of Energy, Energy Information Administration, *Renewable Energy Annual 1995* (Washington D.C.: 1995, accessed February 2004), 35, DOE/EIA-0603(95), available from <http://www.eia.doe.gov/cneaf/solar.renewables/page/pubs.html>; Brad Smith, Forest Inventory Association National Program Leader, email to the author, 25 February 2004).

Green to air dry weight conversion:  $0.623 = \% \text{ wood in green residue} / \% \text{ wood in air dry residue}$   
 $\text{residue} = (100 - 45.4) / (100 - 12.5)$

### Procedures

When each resource potential and distribution had been calculated, I used ArcGIS 8.3 Spatial Analyst raster calculator to aggregate the resources. All resource potential data was previously converted into grid format matching the 400-meter TrueWind Solutions data. I used the raster calculator to sum the monthly resource potential of all five resources for each cell. Using grid rather than polygon format was a purely utilitarian choice. The data and calculations do not require grid format, but by using it I avoided disaggregating polygons into thousands of fragments, and decreased the processing time for calculations tremendously. Grids are also much smaller and more manageable file sizes.

Maps displaying each resource by month, as well as aggregated heating and electric-generation resources are central to the communication of landscape patterns in this study. I built maps with ArcMap 8.3 in a conic-equal area projection, which, by nature, maintains correct areas and minimizes shape distortion at Montana latitudes.

**PART II**  
**RESULTS**

## CHAPTER FOUR

### RESULTS

Results presented in this paper are fundamentally attributable to the assumptions that I have chosen to make about data, technology, and usage. As additional research is completed, it may be appropriate to modify these assumptions to yield a more realistic estimate of resource availability. For example, I have not accounted for the reality that windmills are undesirable, and occasionally illegal in certain areas, or that a high density of wind generators could reduce the overall output by reducing the potential of those positioned downwind. If wind generators were installed at the highest possible density throughout the state, the output would be far less than this data would indicate. These estimates are for each location, *ceteris paribus*. For data available in British thermal units (Btu), I have assumed a conversion technology with an efficiency of 25%. Before utilizing this data for planning or development purposes, these assumptions should be reviewed and modified as necessary for the best possible estimates. Figure 3 is intended to provide reference for maps that follow.



# Montana Reference Map

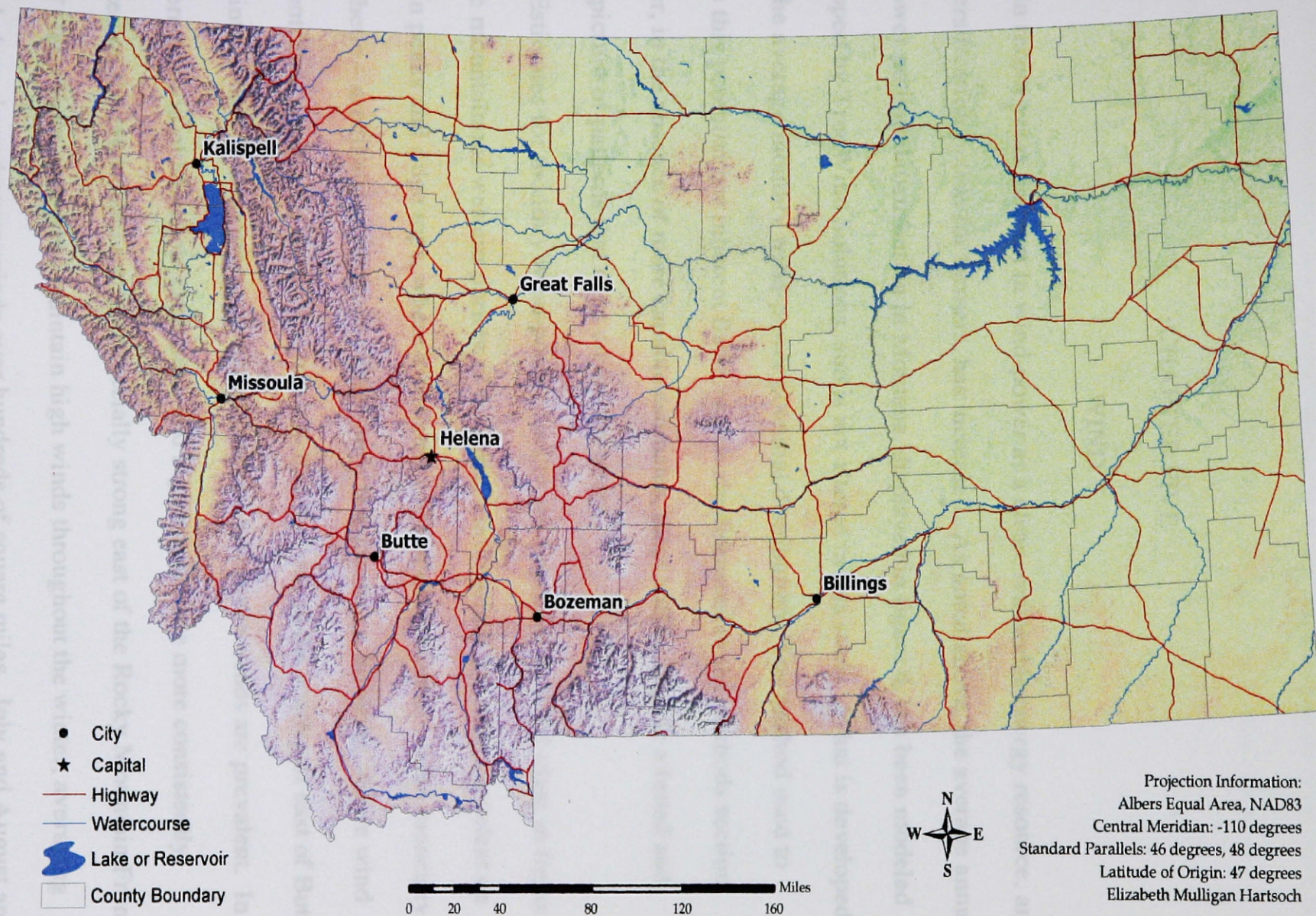


Figure 3

## CHAPTER FIVE

### WIND

In recent years, interest in wind-power as a clean, renewable energy resource, and as a diversification option for farmers, has increased. As noted above, the average annual wind-power potential distribution in Montana, displayed in figure 4, has been modeled and mapped by TrueWind Solutions, and is not altered in this study. What is developed here is the average monthly wind-power potential distribution. The method used to estimate this potential has inherent flaws, which are discussed in the methods section. However, in the absence of more capable estimates, these suffice to give a broad and general picture of patterns that exist on the landscape.

Estimates for monthly wind-power density are displayed by wind-class in figure 5. In the mountainous western portion of the state, usable winds are most prevalent on mountain peaks and ridge tops, where associated costs of development – both monetary and aesthetic – are likely prohibitive. There are a few locations, however, where wind could contribute seasonally to the fuel mix, such as the area to the south and east of Butte in the winter where in December, estimated class six and seven winds are prevalent. In the eastern portion of Montana, class three and higher winds are more consistently distributed on the landscape, and are especially strong east of the Rocky Mountain Front. North of Great Falls, vast areas maintain high winds throughout the winter, averaging estimated class six and seven winds over hundreds of square miles. July and August are

the only months with little wind potential, showing winds estimated to be class three or stronger on ridge-tops and peaks in western Montana, and relatively small areas in eastern Montana.



## Annual Wind Power Density

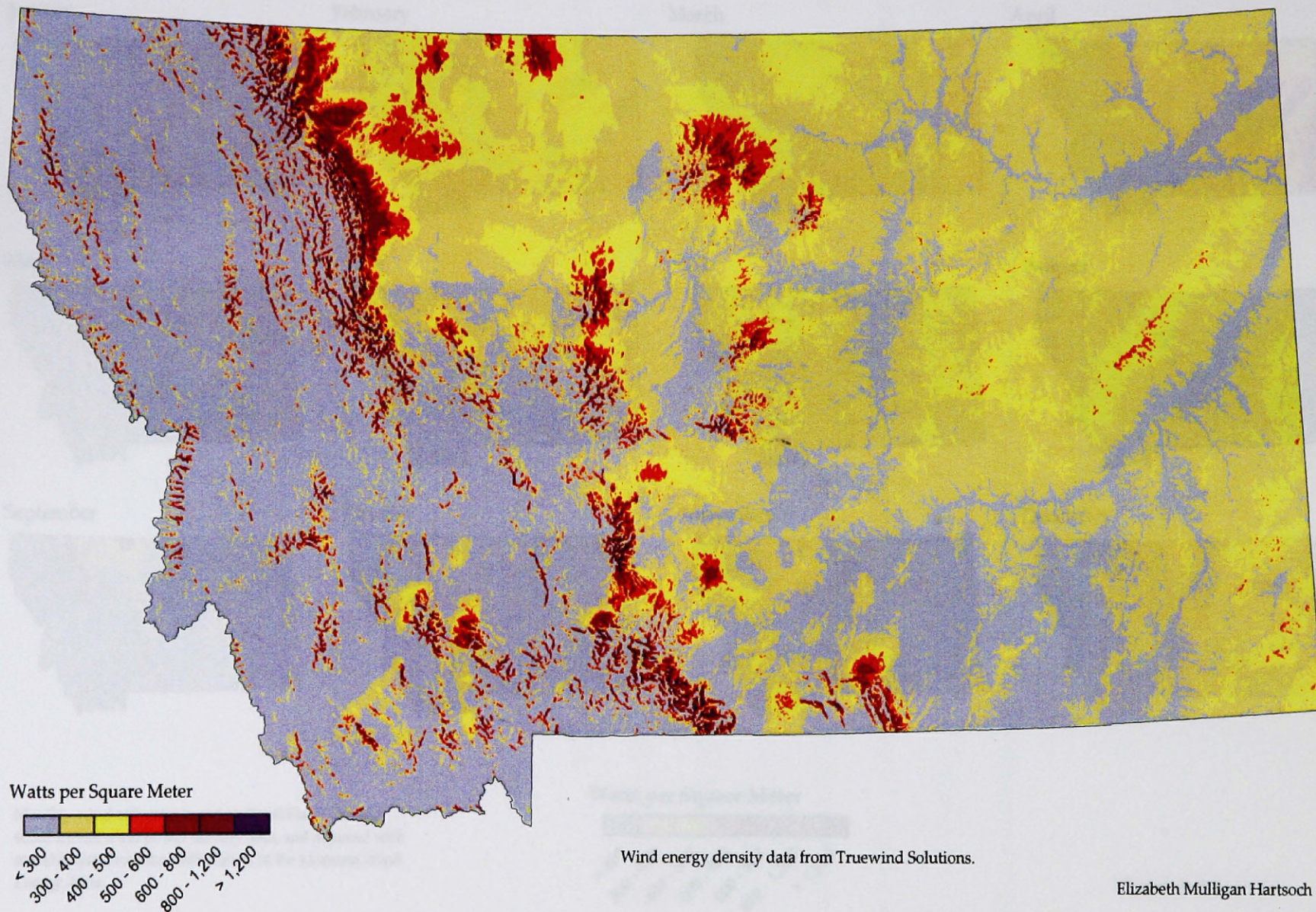
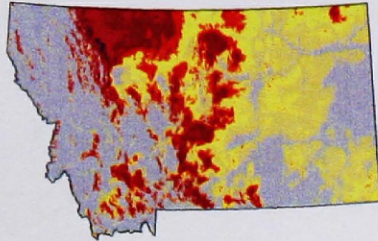


Figure 4

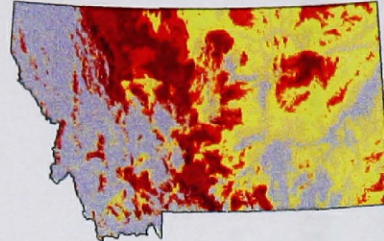


# Monthly Wind Power Density

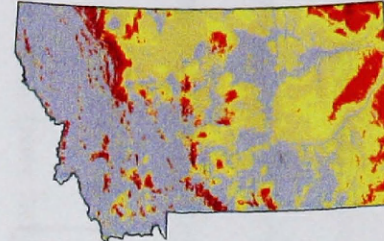
January



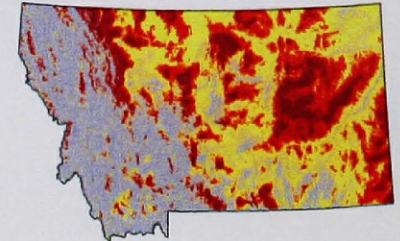
February



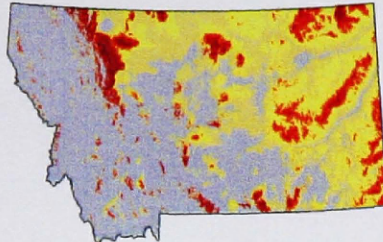
March



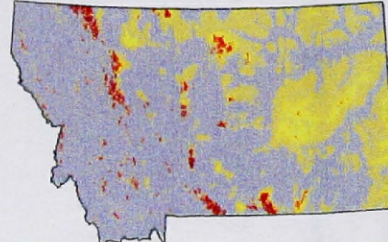
April



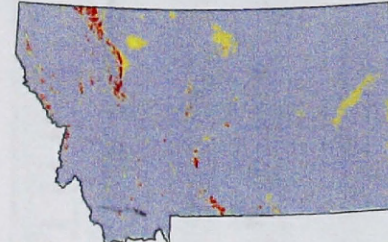
May



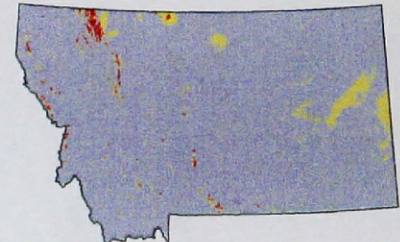
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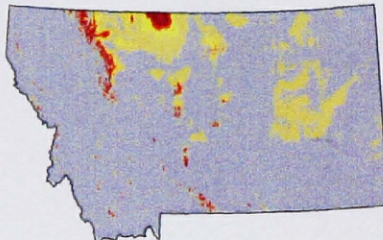
July



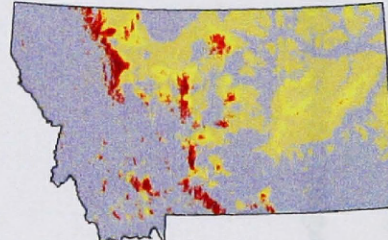
August



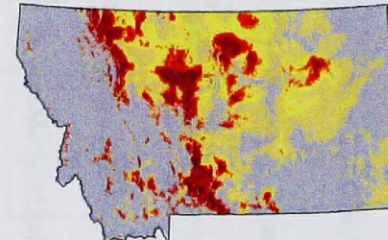
September



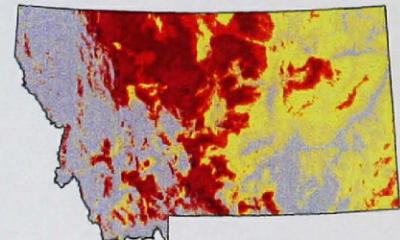
October



November



December



Monthly wind estimates based on TrueWind Solutions 400m annual wind power density data, and adjusted with monthly data from the 1989 edition of the Montana Wind Energy Atlas.

Watts per Square Meter



Elizabeth Mulligan Hartsoch

## CHAPTER SIX

### WATERCOURSES

Throughout the year, watercourse potential is concentrated in the Rocky Mountain region of Montana where both head and rainfall are the greatest. Figures 6 and 7 depict estimated annual and monthly hydropower potential respectively. Seasonally, April and June have the highest hydropower potential estimates, and December and January have the lowest. September through March estimates are relatively constant, however, reflecting the base flow from groundwater percolation. If water is diverted for a 400-meter length of river, capturing the energy available over that section, segments having an estimated potential of 2500 watts per meter could capture one megawatt.



## Annual Watercourse Power Potential

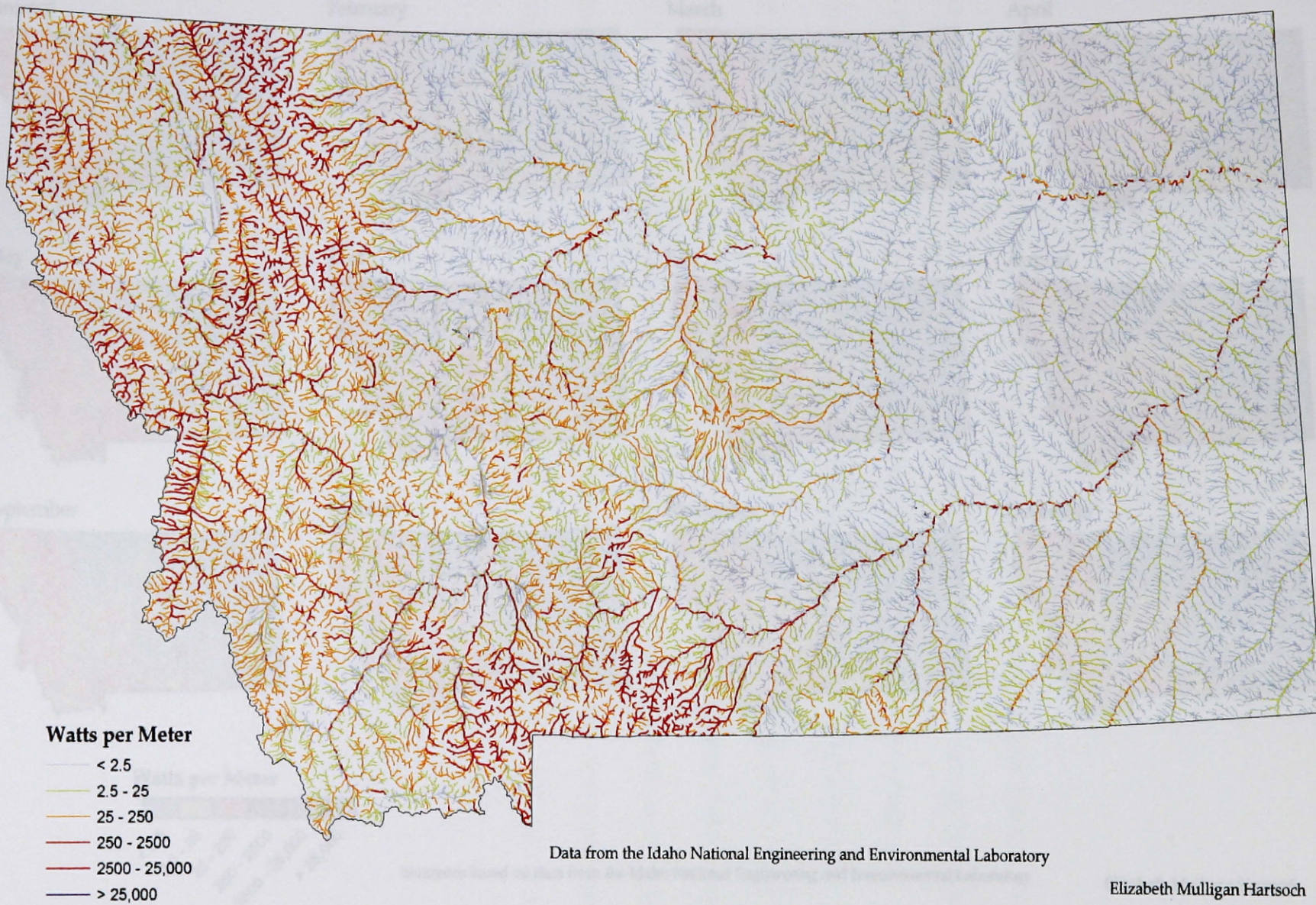
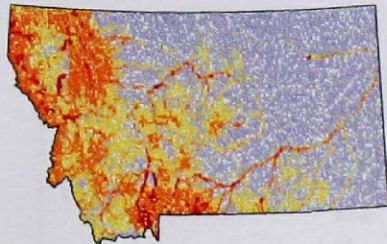


Figure 6

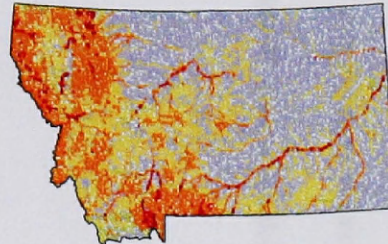


# Monthly Watercourse Power Potential

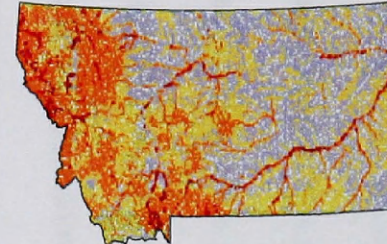
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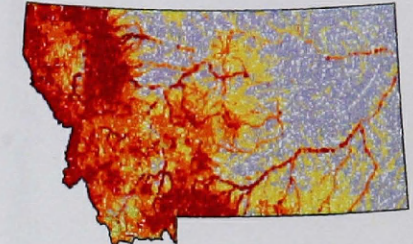
February



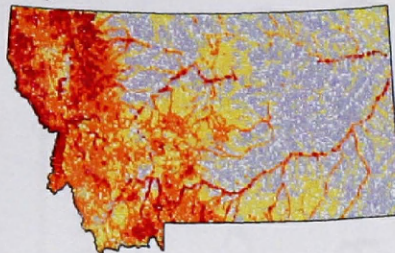
March



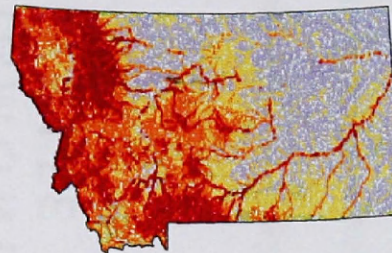
April



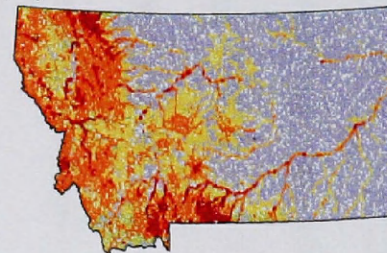
May



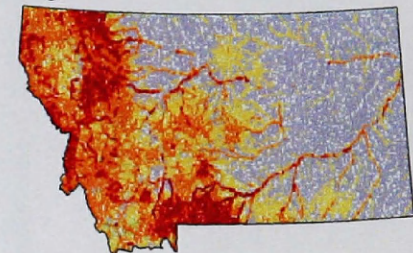
June



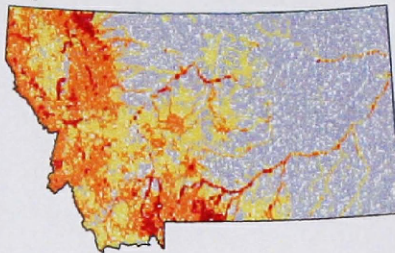
July



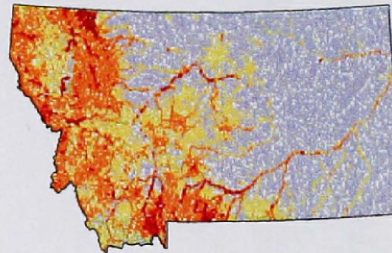
August



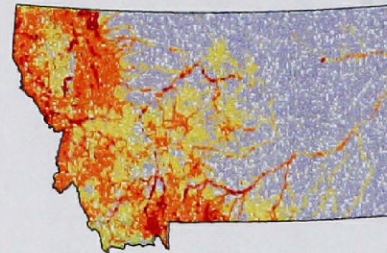
September



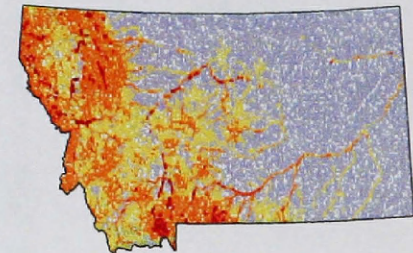
October



November



December



Watts per Meter



Estimates based on data from the Idaho National Engineering and Environmental Laboratory

Elizabeth Mulligan Hartsoch

## **CHAPTER SEVEN**

### **INSOLATION**

Patterns of annual and monthly insolation are shown in maps 6 and 7 respectively. Insolation levels vary seasonally from low levels between 1.6 and 1.7 watts per square meter in December in the northwest portions of the state, to highs over 6.7 watts per square meter in August in southeast Montana. Throughout the year, there is a clear pattern of greater insolation in the eastern portion of the state. June, July, and August receive the most insolation, with state averages of over six watts per square meter, with a high of 6.47 watts per square meter in July. In contrast, December in Montana averages 2.87 watts per square meter, and November also averages less than three watts per square meter. Annual and monthly solar energy density estimates are displayed in figures 8 and 9.



## Annual Insolation Power Density



Insolation data in 40 kilometer grid from the  
National Renewable Energy Laboratory.

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# Monthly Insolation Power Density

January



February



March



April



May



June



July



August



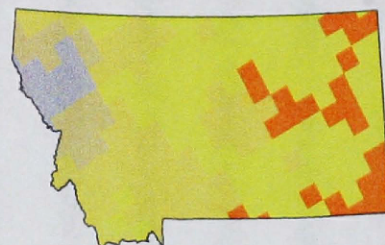
September



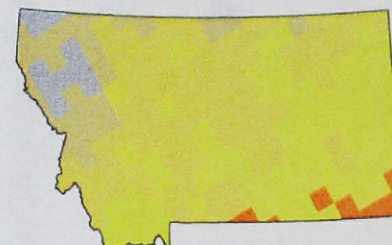
October



November



December



Watts per Square Meter



Insolation data in 40 kilometer grid from the  
National Renewable Energy Laboratory.

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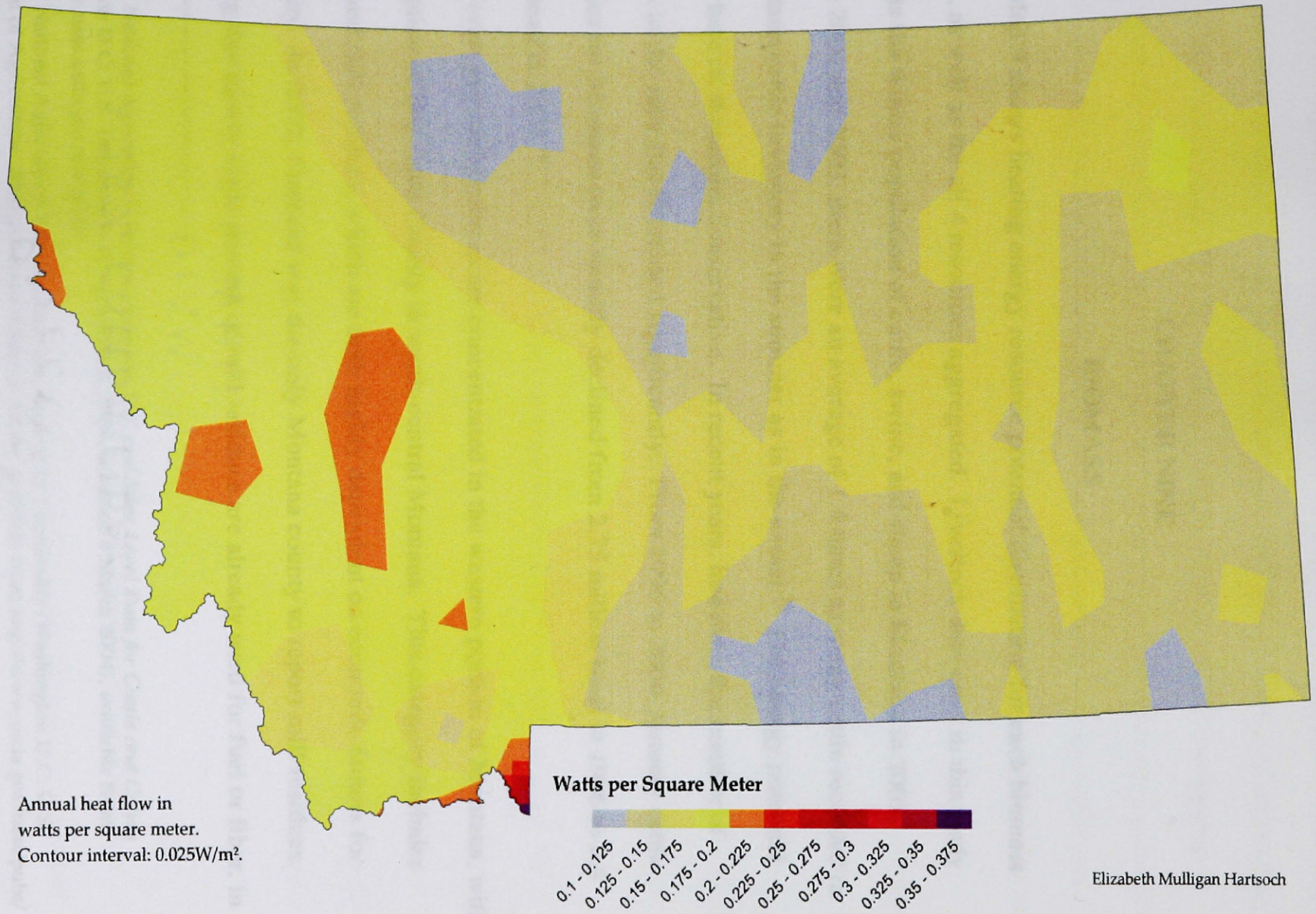
## CHAPTER EIGHT

### GEOTHERMAL

Unlike wind and insolation resources, geothermal potential is more concentrated in the western portion of Montana, especially in a band running east-west through the center, and near Yellowstone National Park. This pattern is shown in figure 10. Yellowstone, of course, is an ecologically and culturally sensitive area that will likely be excluded from development, or heavily restricted. Much of the western portion of Montana has geothermal resources conducive to heating applications, though it is possible that small areas with enough heat flow for electricity generation have been missed by the coarse scale of this data. The *Renewable Energy Atlas of the West* uses a threshold value of 0.150 watts per square meter for electricity production.



# Geothermal Heat Flow



Elizabeth Mulligan Hartsoch

## CHAPTER NINE

### BIOMASS

Map 9 shows heating energy resource potential distribution for each biomass resource, as well as for all 4 resources aggregated. Livestock data used in this study represents the winter population of cattle, swine, and sheep in Montana in 2003.

Between 2000 and 2003, there were an average of 1.4 times as many cattle recorded in the Montana cattle inventory in the summer as in the winter.<sup>75</sup> The energy potential reported here is, therefore, conservative. In recent years, however, the number of livestock in the state has decreased significantly. From 1996 to 2004, January cattle inventories for Montana have steadily declined from 2.75 million head in 1996 to 2.4 million head in 2003.<sup>76</sup>

Forest residue resources are concentrated in the western portion of Montana, with the exception of Big Horn County in south-central Montana. This category includes logging and mill residues, which are both highly dependent on economic factors for availability. In 2002, Flathead was the only Montana county to report mill residues. Assuming that ninety-eight percent of mill residues are already used for fuel or fiber, in

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<sup>75</sup> National Agricultural Statistics Service, *U.S. and State Level Data for Cattle and Calves* (Washington D.C: U.S. Department of Agriculture, 2004, accessed 4 March 2004), available from <http://www.nass.usda.gov:81/ipedb/>

<sup>76</sup> National Agricultural Statistics Service, *Reports by Commodity* (Washington D.C: U.S. Department of Agriculture, 2004, accessed 4 March 2004), available from <http://www.usda.gov/nass/pubs/estindx.htm>.

2002 the remaining two percent amounted to over 658 billion Btu per year in Flathead County. In 2002 Flathead County also reported the most logging residue of any county in the state, equivalent to over 368 billion Btu per year (twenty percent of the logging residue reported), which is still less than half of the available mill residue (two percent of the mill residue reported) in Flathead County. By comparison, the average estimated output of the other forty counties reporting logging residues was forty-six billion Btu per year.

Landfill gas is concentrated near urban centers, and estimated potential is highest in Yellowstone, Missoula, Cascade, and Gallatin counties (Billings, Missoula, Great Falls, and Bozeman respectively). Landfill gas is available in concentrated form at a point source, making it less conducive to the density mapping technique used here. It is likely, however, that these point sources are close to areas of high electric and heating demand, and are, therefore, important considerations in any renewable energy-development strategy. This assumption is supported by the pattern of data, since the counties with high landfill gas potential have large urban centers.

Spatially, livestock waste is more difficult to generalize than other biomass resources. Counties with the highest concentration of livestock waste resources include Lake and Cascade, with over four kilowatts per square kilometer. Counties in the top five for livestock waste potential density span the state, and are often bordered by counties with much lower density.

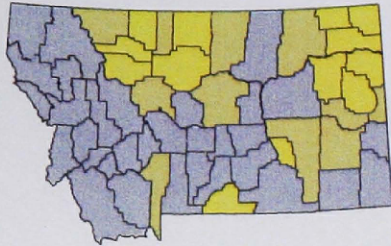
Counties with the highest density of agricultural residue energy potential are concentrated in the northeast corner of Montana, with Sheridan, Daniels, Richland and Roosevelt estimated at the highest densities in the state, at nearly or greater than  $1 \times 10^3$

watts per square meter. They are followed by north-central counties Pondera and Hill, with over  $8 \times 10^{-4}$  watts per square meter. Patterns of distribution are displayed in figure 11.

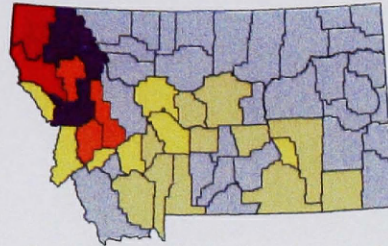


# Biomass Resource Density

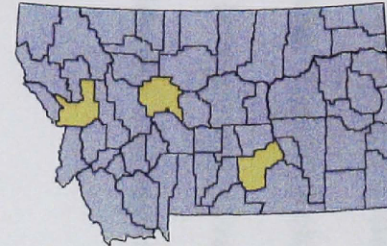
Agricultural Residues



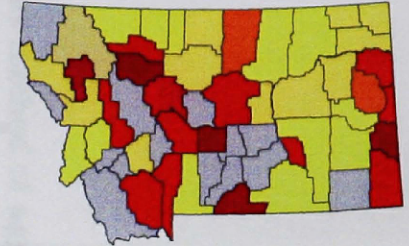
Forest Residues



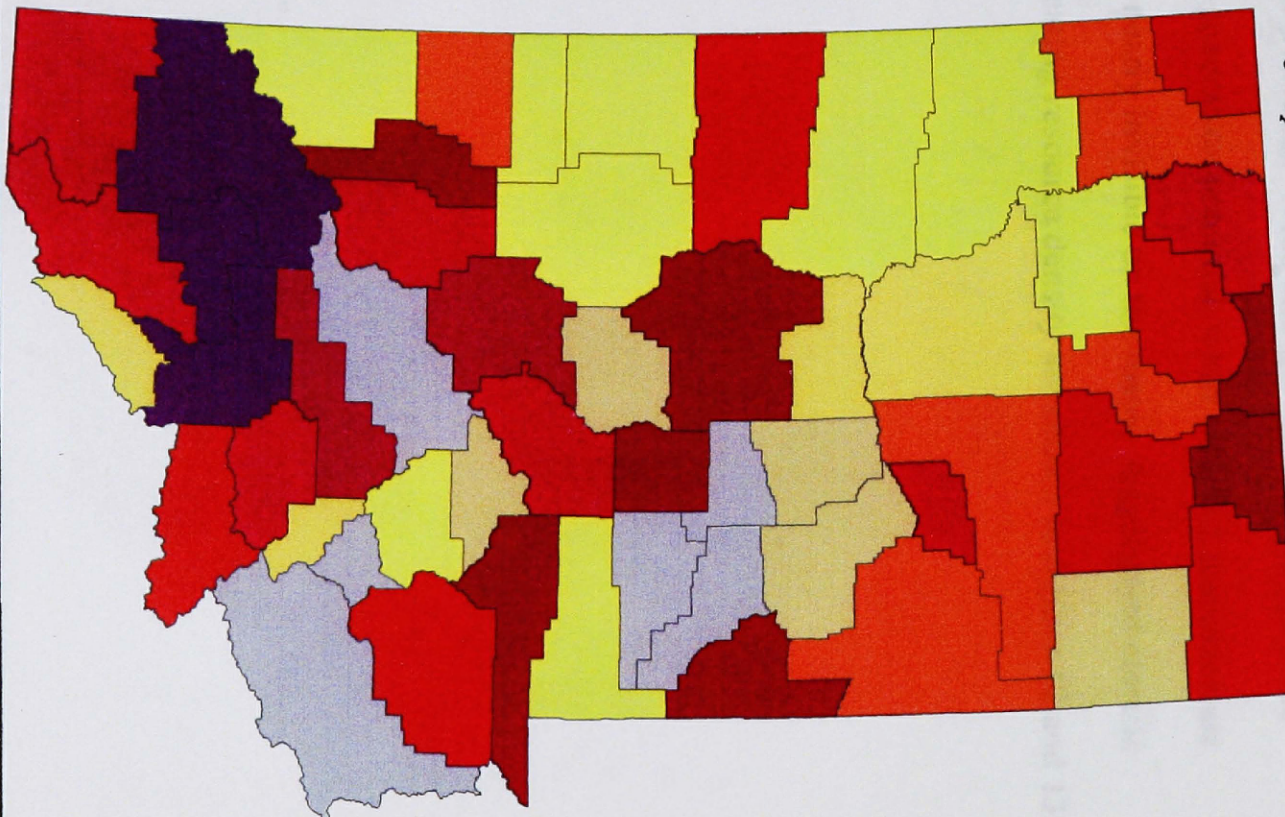
Lanfill Gas



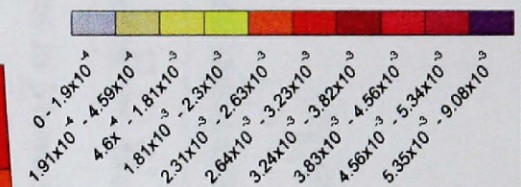
Livestock Waste



Aggregated Biomass Resource Density



Btu / Hour / Square Meter



Annual average energy density in Btu/h/m<sup>2</sup> by county. Aggregate biomass resource density is the sum of individual resources for each county.

Elizabeth Mulligan Hartsoch

## **CHAPTER TEN**

### **AGGREGATED RESOURCES**

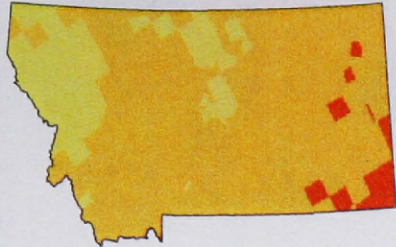
**This method of aggregating resources was successful in highlighting those resources that are most abundant in Montana. Wind and watercourse potential are apparent with regard to electricity-generation potential, while all other resources are present at low enough levels to be nearly invisible on the maps. Aggregated electric resource density and aggregated heating resource density are shown in figures 12 and 13.**



# Aggregated Heating Resource Density

Including insolation, geothermal and biomass

January



February



March



April



May



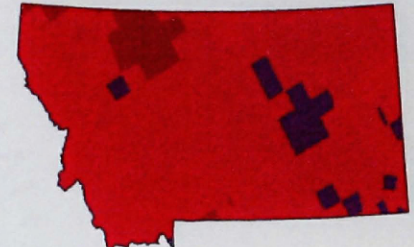
June



July



August



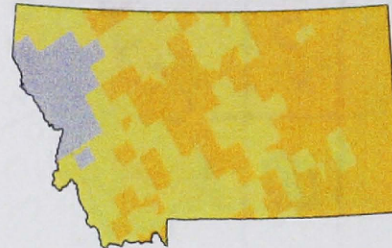
September



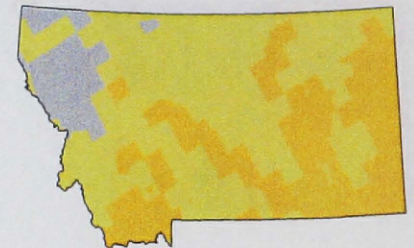
October



November



December



Btu / Hour / Square Meter



30 - 40  
40 - 50  
50 - 60  
60 - 70  
70 - 80  
80 - 90  
90 - 100  
100 - 110

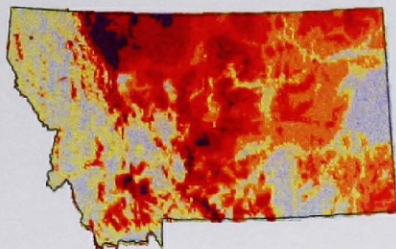
Elizabeth Mulligan Hartsoch



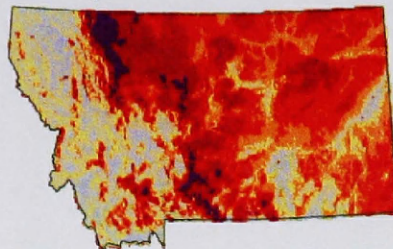
# Aggregated Electric Resource Density

Including all resources.

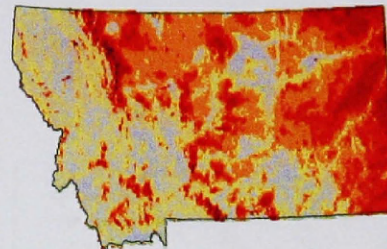
January



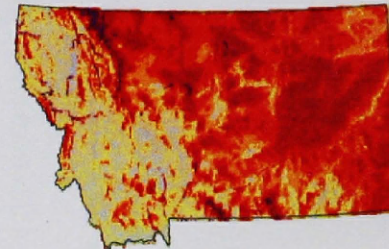
February



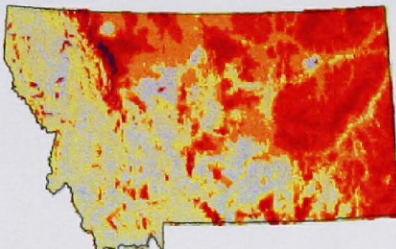
March



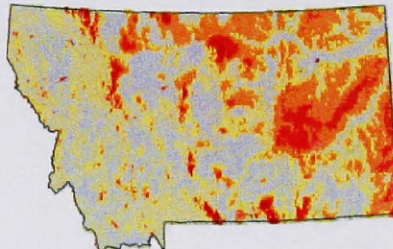
April



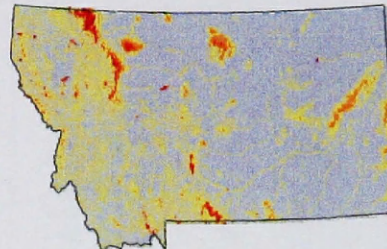
May



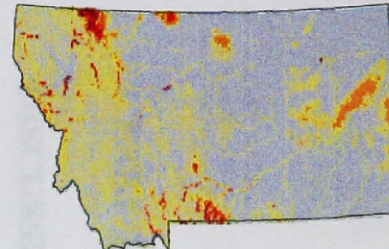
June



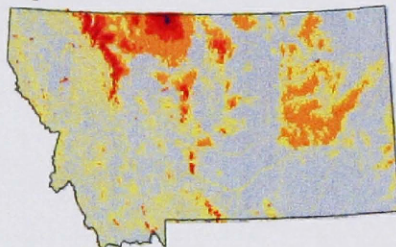
July



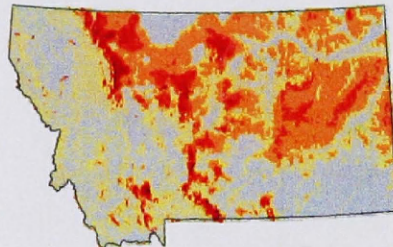
August



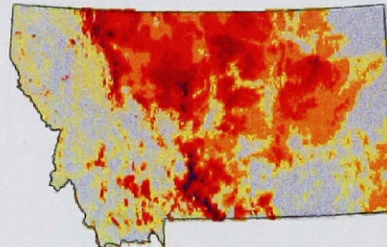
September



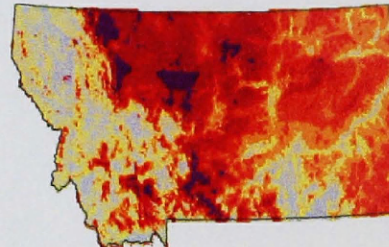
October



November



December



Watts per Square Meter



Elizabeth Mulligan Hartsoch



**PART III**  
**DISCUSSION**

## CHAPTER ELEVEN

### HEATING RESOURCE POTENTIAL

Seasonal distribution of heat-energy potential, measured in British thermal units, is largely composed of solar-energy potential, with geothermal potential a close second, and biomass a distant third. Since the potential of solar resources is seasonal, while geothermal and biomass are assumed to be constant, the relative importance of the latter two resources is greater in the winter months when insolation is low. Montanans need heating resources in the winter, when they are most scarce. In fact, the demand for heating resources in the winter is a result of lower levels of insolation. In the summer, Montanans are already taking advantage of insolation, both passively and actively. To plan for annual fluctuation in resource availability, the annual average heating potential of resources is inadequate, and monthly estimates are necessary. December has the lowest resource potential for any month in Montana, with an average of forty-eight Btu/h per square meter across the state. It is also the second coldest month, with an average temperature of twenty-one degrees over the past fifty years.<sup>77</sup> Biomass is a good complement to insolation because biomass resources can be stored – either directly or when converted to higher quality fuel – throughout the year and utilized in the winter

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<sup>77</sup> National Oceanic and Atmospheric Administration, *Climate at a Glance* (Asheville, North Carolina: National Climatic Data Center, 2004, accessed 29 April 2004), available from <http://climvis.ncdc.noaa.gov/cgi-bin/cag3/hr-display3.pl>.

when solar resources are lowest. The annual average Btu/h potential of biomass in Montana is approximately  $3 \times 10^3$  per square meter. If biomass resources were stored for use in the three months of the year with the greatest disparity between heating use and solar resource, the biomass potential estimate would be  $1.2 \times 10^2$  Btu/h per square meter, 300% greater than if the resource potential were distributed throughout the year. Compared to the December average insolation of forty-eight Btu/h/m<sup>2</sup>, this biomass potential seems small. Biomass, however, has the advantage of being both storable and transportable. The entire biomass potential, minus storage and transportation losses, could be used where it is needed. At some threshold, the cost of transportation and storage would outweigh the benefit of having the fuel where and when it is needed. Calculating this threshold, however, requires numerous assumptions about market conditions that are beyond the scope and concern of this study.<sup>78</sup>

Insolation is the most available resource for heating energy, but, as noted above, it is seasonally low in the winter when heating needs are greatest, and it is not easily stored or transported as a fuel. Insolation is appropriate for both heating and electric-generation scenarios. This resource might be most effectively utilized in Montana through a combination of household/individual unit scale heating applications, and mid-scale distributed electric-generation facilities. Heating systems can be designed to capture heat

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<sup>78</sup> For further discussion of this matter, refer to James D. Kerstetter and John Kim Lyons, *Logging and Agricultural Residue Supply Curves for the Pacific Northwest* (Pullman: Washington State University Energy Program for the United States Department of Energy, 2001), Contract # DE-FC01-99EE50616, and Marie E. Walsh, Robert L. Perlack, Anthony Turhollow, Daniel de la Torre Ugarte, Denny A. Becker, Robin L. Graham, Stephen E. Slinsky, and Daryll E. Ray, *Biomass Feedstock Availability in the United States: 1999 State Level Analysis* (Oak Ridge, Tennessee: Oak Ridge National Laboratory, 2000).

in the cold months, and solar electric is an excellent compliment to wind-power, which peaks in the winter.

Landfill gas appears to make a minimal contribution to the total heating resource, but given the close proximity of most landfills to urban centers, they are ideally located to contribute to the fuel mix. The Department of Energy Landfill Methane Outreach Program assists landfills with potential of more than one megawatt that are interested in capturing and utilizing landfill gas. Smaller sites across Montana may benefit simply from using the landfill gas to heat their facilities, or nearby greenhouses.

## CHAPTER TWELVE

### ELECTRIC-GENERATION POTENTIAL

All five resources were aggregated to estimate electricity-generation potential. It is apparent in the maps that wind and watercourse resources are widely available, and in many cases compliment each other spatially as well as seasonally. Throughout the state, high watercourse potential is often found in areas of low wind potential. In the Rocky Mountain region of Montana, where wind is prevalent on ridges and hilltops, which are often undesirable locations for development, watercourses in the ravines and valleys, which have historically been popular for human settlement, are a promising alternative. In fact, the pattern of watercourse resource potential across the state is nearly opposite that of wind-resource potential, with much greater watercourse potential in the mountains.

Insolation, geothermal and biomass electric-generation potentials are overpowered in the aggregate map by wind and watercourse resources. They will likely still be locally important, however, in areas where wind and watercourse resources are unavailable or restricted. In many locations, however, these resources may be more efficiently used for heating applications.

To highlight the potential for complementary renewable resources in distributed generation scenarios, I have chosen a location in Montana for further discussion. Sula,

Montana is in the mountainous western portion of the state, at the southern end of the Bitterroot Valley, just northwest of the Idaho border, with geographic coordinates of roughly 46 degrees north latitude and 114 degrees west longitude. Throughout the year, the East Fork of the Bitterroot River could generate electricity for Sula. Spring flow estimates in April and June exceed two thousand watts per meter, the annual average estimate is 662 watts per meter, and the lowest estimates in the winter months are over 150 watts per meter. Insolation peaks in July and August with over six watts per square meter. Wind at usable levels is only available locally on ridges and peaks, making it an unlikely player in Sula's energy-resource mix, though power-lines could deliver electricity from wind generators in the winter, when wind is most prevalent across the state and insolation and hydropower are low in Sula. Relative to the rest of Montana, Sula has a moderate estimated geothermal potential of between 0.175 and 0.2 watts per square meter, which could contribute to water- or space-heating applications. Ravalli County, including Sula, has an annual average biomass potential of  $3 \times 10^{-3}$  Btu/h/m<sup>2</sup>, largely composed of forest residues and livestock waste, which could be stored for use in the fall and winter when heating needs are high and seasonal resources are low.

## **CHAPTER THIRTEEN**

### **FUTURE RESEARCH**

In the process of writing this paper, I have identified several areas that are in need of further study.

Logging and mill residue availability is highly dependent upon economic factors. Regulations, the market price of timber, and the strength of the US dollar all play a role in the profitability of logging and milling operations. Incorporating a model to predict aspects of this, such as which mills will be open and how much timber will be cut, could greatly improve these results. Current efforts to curb wildfires through fuel reduction programs could create an additional source of forest residues for energy generation.

Annual wind and watercourse potential estimates are well developed, but seasonal or monthly potential have not been estimated. I have made estimates for the purposes of this study, but there is room for improvement. While the most appropriate entity to estimate seasonal wind potential is TrueWind Solutions, a private company with proprietary modeling techniques, the watercourse estimates will likely be made by the Idaho National Engineering and Environmental Laboratory, the federal laboratory responsible for the annual estimates. INEEL has expressed interest in working with students and faculty on related projects.

The Sula example highlights the need for further information about the amount of acceptable land and air space that could be committed to energy capture and conversion, as well as the patterns of energy use in Montana. The information in this paper allows speculation on what might be used to meet the needs of Sula, but it says nothing of Sula's needs. Further work in this area will be very helpful in completing the picture of resource complementarity and energy quality matching.



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